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OPTICAL TECHNIQUES FOR MILLIMETER-WAVE PHASED ARRAY COMMUNICATIONS ANTENNAS

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13. ABSTRACT *(Maximum 200 words)*

The scope of this program was to study the application of optical techniques to signal distribution and beamforming networks in phased array antennas for Army mobile tactical communications systems, with the aim of identifying advantagous system architectures. This study included systems operating at 9 GHz (original frequency for the Radio Access Point), 20/44 GHz (for SATCOM applications) and 55 GHz (for vehicle-to-vehicle line-of-sight). As a result of this study experimental optical modules were designed, fabricated and delivered. The optical modules were designed to achieve the basic functions of an optical beamforming system for the Radio Access Point. The four modules included a quadrature phase shift keying (QPSK) coder with optical splitter/beamformer, optical single sideband modulator/beamformer and optical multi-input receiver.

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LIST OF MAJOR ABBREVIATIONS USED

CNR   Ratio of mean carrier power to noise density (dB Hz)
CPW   'Co-planar waveguide'
DFB   'Distributed feedback'
DSB   'Double sideband'
ECL   'Emitter Coupled Logic'
EDFA   'Erbium doped fiber amplifier'
EHF   'Extra High Frequency'
EIRP   'Equivalent isotropic radiated power'
FM   'Frequency Modulation'
FSK   'Frequency shift keying'
IF   'Intermediate Frequency'
IMD3   Third order intermodulation product from two equal power tones (dBc)
LED   'Light Emitting Diode'
LNA   'Low noise amplifier'
MIR   'Multi-Input Receiver'
MMI   'Multi-mode Interference'
MMIC   'Monolithic Microwave Integrated Circuit'
NF   Noise figure of a microwave link (dB)
OEIC   'Optoelectronic Integrated Circuit'
OPLL   'Optical Phase Locked Loop'
PM   'Polarization Maintaining'
PMF   'Polarization maintaining fiber'
PSK   'Phase Shift Keying'. Data modulation format
QAM   'Quadrature Amplitude Modulation'
QPSK   'Quadrature Phase Shift Keying'
RAP   'Radio Access Point'
RF   'Radio Frequency'
RIN   'Relative intensity noise'
RMS   'Root mean square'
Rx   Receive
SFDR   'Spurious free dynamic range'
SHF   'Super High Frequency'
SM   'Single mode'
SMF   'Single mode fiber'
SOA   'Semiconductor optical amplifier'
SSB   'Single sideband'
T/R   'Transmit receive'
TE   'Transverse Electric'
TM   'Transverse Magnetic'
TTD   'True time delay'
Tx   Transmit
VSWR   'Voltage standing wave ratio'
WDM   'Wavelength division multiplexing'

YAG   'Yttrium Aluminium Garnet'

Optical Techniques for Millimeter-Wave Phased Array Communications Antennas (OPTEMAS)

Final Report

1. INTRODUCTION

The scope of this program was to study the application of optical techniques to signal distribution and beamforming networks in phased array antennas for mobile communications, with the aim of identifying advantageous system architectures. This study included systems operating at 9 GHz, 20/44 GHz and 55 GHz. As a result of this study experimental optical modules were designed, fabricated and delivered to US Army CECOM as an experimental subsystem.

The study and experimental work performed in this program followed the tasks described in the original white paper [1]. The results are described in five technical reports [2-6] which are summarized in this final report. The chapter and section headings of this report reflect the work packages and task descriptions from the original white paper.

2. ARCHITECTURE STUDY

The first part of the program was to perform a detailed study into the suitability of alternative optical distribution and beamforming techniques for use in phased array antennas for land-based mobile communication applications. The results of this study are detailed in two reports.

The 'Systems Architecture Study' report [2] identifies the critical system requirements and describes alternative optical architectures which could be used to achieve them. This report includes a detailed mass and power trade-off analysis of various optical architectures, from which the most suitable link designs are identified. These results of this work are summarized in sections 2.1 to 2.4.

The 'Technology Study' report [3] discusses the optoelectronic components required for the proposed link designs, the packaging and interfacing technologies, the possible use of monolithic integration and the effect of environmental factors on the performance of an optically controlled phased array system. These aspects are summarized in sections 2.5 to 2.7.

2.1 Candidate System Definition

In close collaboration with the sponsor, three alternative phased array systems were specified, the basic performance requirements of which are summarized in table 2.1.

The Radio Access Point (RAP) is a vehicle-to-vehicle line-of-sight SHF communication link and is the system on which the analysis was concentrated. The antenna requirements were based on an application being actively investigated by CECOM and as such its specifications evolved during the study. The 'Modified RAP' system is the more recent variant which has some significant differences such as the data format, transmit EIRP and receive dynamic range.

Antenna	RAP	Modified RAP	EHF RAP	SATCOM (Milstar) (TX / RX)
No. antenna elements	256	256	256	~2000
Min. antenna gain	24 dB	24 dB	24 dB	33 dB
Element spacing	17.5 mm	20 mm	3.4 mm	3.3 mm / 7.0 mm
Carrier Frequency	9±2 GHz	7.5±0.5 GHz	55±3 GHz	44 GHz / 20 GHz
Max. scan angle: altitude	±30°	±30°	±30°	±80°
Scan resolution: altitude	5-bit	5-bit	5-bit	8-bit
Max. scan angle: azimuth	±50°	±50°	±50°	±80°
Scan resolution: azimuth	6-bit	6-bit	6-bit	8-bit
Sidelobe level	-15 dB	-15 dB	-15 dB	-25 dB
Modulation Data				
Data format	64-QAM	QPSK	QPSK	FSK (CDMA)
Data rate	155 Mb/s	45 Mb/s	20 Mb/s	2.4 kb/s
Instantaneous bandwidth	30 MHz	40 MHz	20 MHz	100 MHz
Max. carrier linewidth	10 kHz	3 kHz	1.5 kHz	5 Hz
Transmit Link				
Min. EIRP (per beam)	34 dBW	24 dBW	34 dBW	47 dBW
Min. CNR	120 dB Hz	105 dB Hz	100 dB Hz	100 dB Hz
Linearity	0.1 dB comp.	1 dB comp.	1 dB comp.	-30 dBc (IMD3)
Receive Link				
Maximum noise figure	8 dB	8 dB	8 dB	8 dB
Min. G/T	-8.6 dB	-8.6 dB	-8.6 dB	+0.4 dB
Min. SFDR	80 dB	60 dB	80 dB	60 dB
Others				
No. antenna panels	4	4	4	1
No. independent beams	2	2	3	1
No. channels / beam	1	1	1	2
Reprogramming interval	1 µs	10 µs	10 µs	1 µs

Table 2.1: Summary of the four phased array communication antennas considered in the Architecture Study

The two millimeter-wave systems, 'EHF RAP' and 'SATCOM', are longer term requirements and as such their performance specifications were less well defined. The 'EHF RAP' is a vehicle-to-vehicle line-of-sight communications link operating at 55 GHz, in the wings of the Oxygen absorption spectrum, thereby limiting the transmission range. This allows extensive re-use of frequencies in a cellular network and also provides a degree of intrinsic security from interception. The SATCOM system is a mobile vehicle based satellite link using the Milstar standard with 44 GHz uplink and 20 GHz downlink. Due to security restrictions the full Milstar specification was not available to GMMT in time for this analysis. The assumptions which were made are detailed in table 2.1.

Although all four systems specified in table 2.1 are mobile communication links with broadly similar functionality, the differences in their performance and operational requirements are significant enough to impact the choice of optimum optical link architecture. The link analysis, summarized in section 2.4, therefore considered each system independently.

2.2   Architectures for Signal Distribution

The block diagram of a generic transmit / receive link for an active phased array antenna is illustrated in figure 2.1. In the transmit link the microwave carrier is modulated with the data, a portion of which is distributed to each antenna element. A controlled phase shift and amplitude attenuation is imparted in the beamformer. Within each transmit antenna module the signal is amplified before being transmitted by the antenna element.

The configuration shown in figure 2.1 assumes that the same antenna element is used for simultaneous transmit and receive operation, a circulator being used to isolate the two links. The required isolation is often higher than can be achieved with a single circulator therefore additional isolation or separate transmit and receive antennas may be required. The receive signal from each antenna element is amplified in a low noise amplifier (LNA) before passing through its own beamformer (phase and amplitude control). The received signals from each antenna element are combined and the resulting summed microwave signal is demodulated to generate the received data.

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In addition to the distribution and beamforming links it is necessary to have a data link to distribute data to each beamformer to control its phase and amplitude settings.

Figure 2.1 is a general diagram and in practice many variations are used. Some phased array systems distribute a microwave LO signal to the transmit modules, the beamforming being applied to an IF signal, with the up-conversion occurring within the transmit module. A similar, reciprocal design could also be employed in the receive link.
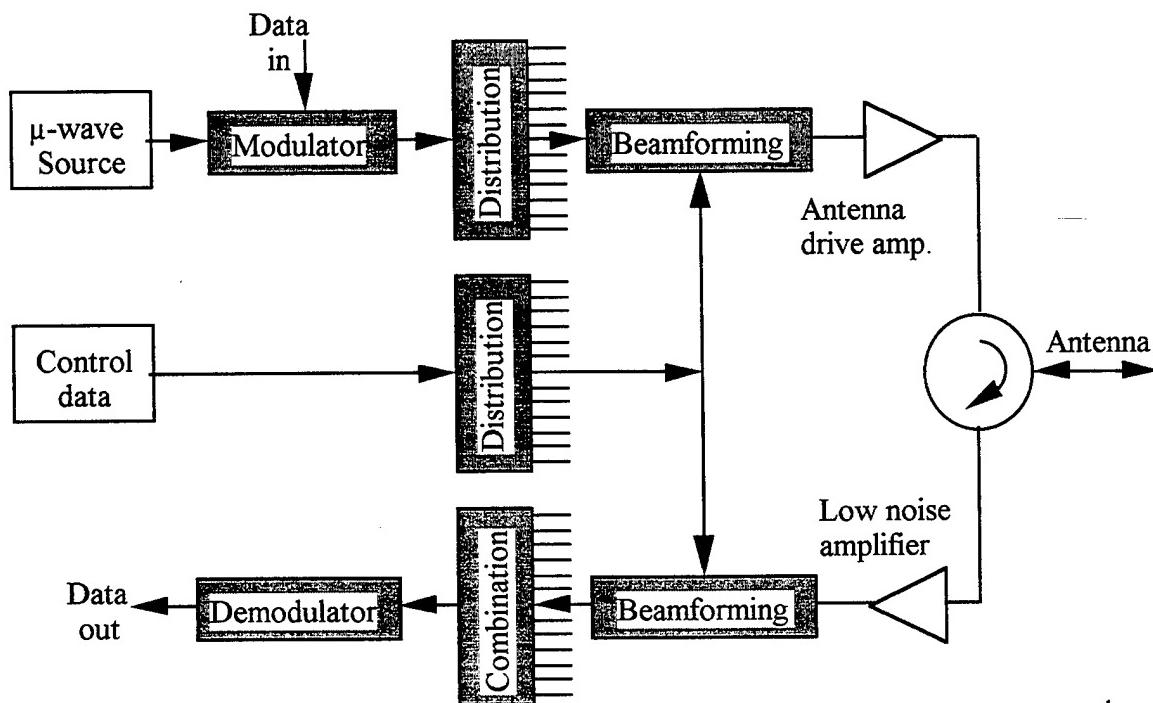
Fig. 2.1: Block diagram of a basic phased array transmit / receive link

The shaded blocks in figure 2.1 are functions which could, in principle, be performed optically. This section describes possible architectures for the optical distribution of the control data and microwave signals. Optical beamforming designs are discussed in section 2.3.

2.2.1 Distribution of Control Data

In a conventional active phased array antenna, the microwave beamforming functions (phase and amplitude control) are positioned in the T/R modules immediately behind the radiating antennas. A data distribution link is therefore required from the control computer to each beamforming component. An optical fiber link is very attractive for this application due to its high data capacity, low weight, flexibility, and low crosstalk. The advantage of such an approach over a simpler, lower cost, twisted pair electrical link is dependent on the data rate to be transmitted.

The RAP system requires 11 bits of data to provide the complete beampointing information (6-bit azimuth, 5-bit altitude). Assuming a framing overhead of 5 bits the total beampointing data becomes 16 bits. With a minimum reconfiguration time of 1 μs, the maximum data rate required to transmit this beampointing information is 16 Mbit/s. This information can only be used if each beamformer has its own calibration and phase settings stored locally. To transmit the full phase setting data to each beamformer in a single serial link the maximum data rate for the 256 element RAP antenna becomes 4.1 Gbit/s.

A very low data rate control is possible if the antenna always performs a simple uniform scan. In this case the only commands required will be to increase or decrease the beam direction in altitude or azimuth. This requires significant processing power within each beamformer and is less flexible than the other approaches, but could be achieved with only 2 data bits per update time interval.

Table 2.2 summarizes the serial data rates of four alternative control options for each of the antenna systems being considered. These data rates are for a single beam only; multi-beam systems will require an identical data link for each independent beam.

Data Type	RAP	Mod. RAP	EHF RAP	SATCOM
Separate TX & RX phase data	8.2 Gbit/s	8.2 Gbit/s	0.82 Gbit/s	86 Gbit/s
Common TX & RX phase data	4.1 Gbit/s	4.1 Gbit/s	0.42 Gbit/s	43 Gbit/s
Beampointing data only	16 Mbit/s	16 Mbit/s	1.6 Mbit/s	21 Mbit/s
Beam update data only	2.0 Mbit/s	2.0 Mbit/s	0.2 Mbit/s	2.0 Mbit/s

Table 2.2: Data rates for four alternative control options

A basic electrical data link is limited to about 0.2 Gbit/s and in duplex or multi-beam systems crosstalk between the different links must be carefully avoided. The simplest, lowest cost optical data link, based on an LED source and a multi-mode fiber, is capable of transmitting up to 0.2 Gbits/s over short distances (~10 m). Using single-mode fiber and semiconductor lasers data rates of 1 Gbit/s are relatively straightforward. 2.5 Gbit/s is now a standard optical data link and components for 10 Gbit/s systems are also available.

In conclusion, to transmit only beampointing information a simple electrical link can be used, but processing will be required at each beamformer. To transmit all of the beamformer data requires a high data rate optical link, or even several parallel optical links for large arrays. This approach removes the need for processing in the beamformer but will require demultiplexing of the serial data within the antenna unit and a low data rate backplane to distribute the control signals to each beamformer.

A further advantage of using an optical data link is that, in some link designs, optical multiplexing could be used to distribute both the control data and microwave signal to the antenna modules over the same optical network.

The previous discussion has assumed that the beamformers are situated within the antenna unit, thereby requiring the control data to be transmitted some distance from the beamforming computer. As will be described in the following section, if optical fibers are used for the microwave links it is

possible to move the beamformers away from the antenna unit, closer to the beamforming computer, where a simple, parallel backplane link can be used to distribute the control data.

2.2.2 Distribution of Microwave Signal

The advantages of using optical fibers to distribute microwave signals are now well known. The links can have a very wide bandwidth due to their low, frequency independent loss and negligible dispersion. Optical fiber cable is also more flexible and compact and has lower mass than its electrical equivalent. In addition optical fiber has a much lower thermal expansion than co-ax or waveguide making its time delay less sensitive to environmental fluctuations, and being an optical medium it is effectively immune to electromagnetic interference and crosstalk effects. Wavelength multiplexing approaches can also be used to transmit several independent signals along a single optical fiber. Many of these features offer a significant advantage in a phased array antenna system, in particular the improved environmental phase stability which makes it possible to optically remote the distribution and beamforming functions away from the antenna panel.

A simple optical microwave link can be achieved in one of two ways, by employing either intensity modulation or optical heterodyne signal generation, as illustrated in figure 2.2. In the former the transmitter modulates the intensity of the optical source with the required microwave signal, either by direct laser modulation or an external optical modulator. The latter approach is more common at microwave frequencies since the bandwidth, efficiency and linearity can be optimized independently of the optical power and optical noise. The modulated optical signal is transmitted over a length of low loss, single-mode optical fiber to the photo-receiver where it is converted to a modulated photocurrent and hence regenerates the original microwave signal. The gain of such a link is dependent on the optical power, the optical loss of the link and the efficiency of the modulator and photo-receiver. Such designs are suitable for the optical distribution of the LO, microwave or IF signals in the transmit and receive links of a phased array antenna system.

The heterodyne approach is, in effect, a single-sideband (SSB) optical link, whereas the intensity modulated approach is a double-sideband (DSB) system. The approach illustrated in figure 2.2 uses a

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transmitter to generate two coherent, frequency shifted optical signals (carrier plus sideband). This transmitter could be a dual-mode laser, two injection locked lasers, two phase locked lasers or an optical source followed by a single-sideband optical modulator. At the photo-receiver the two optical signals generate a beat signal at their difference frequency, thereby producing the desired microwave signal. Such a technique can be more efficient than an intensity modulated link and is particularly suitable for the optical transmission of millimeter-wave signals over long distances where the double-sideband approaches suffer from signal attenuation induced by optical dispersion. Efficient generation of two optical signals with the desired phase coherence is considerably more complex than simple intensity modulation of a laser source.

Such a link design is, however, necessary in order to use the optically controlled phase shift beamforming architectures discussed in section 2.3.
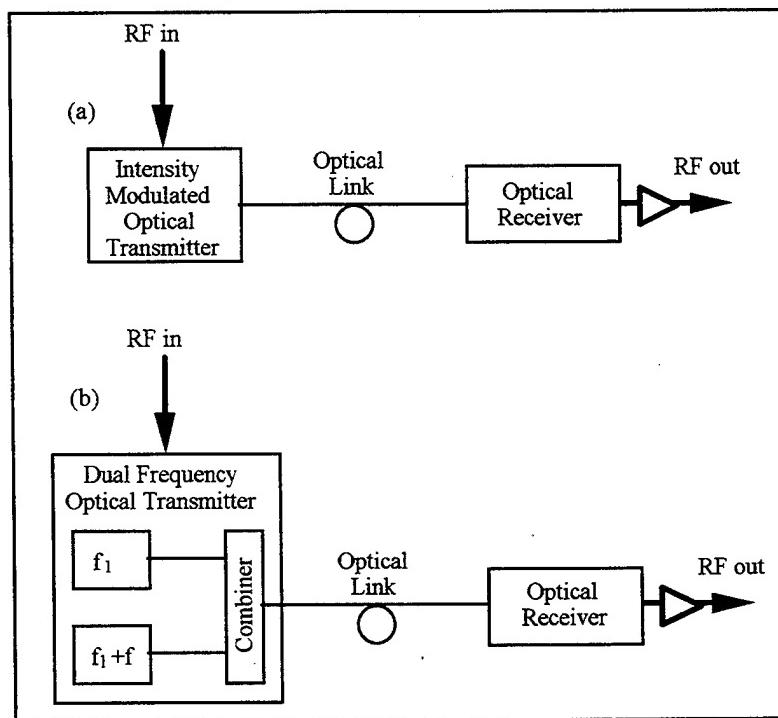
Figure 2.2: Two basic types of optical microwave link
(a) intensity modulated link
(b) optical heterodyne link

Dual-source transmitters based on phase or injection locking produce an output signal which is effectively independent of the power of the input microwave signal, which has only to be large enough to maintain the desired frequency lock. This approach is suitable for the distribution of an LO signal or a fixed power microwave signal to the transmit antenna array. An external single-sideband optical modulator, on the other hand, imparts the amplitude, phase and frequency of the applied microwave signal onto the optical sideband, thereby producing a linear microwave link. Although this is usually less efficient the linearity it provides is essential in many link architectures, particularly in receive-mode links using heterodyne optical RF beamforming. This point is discussed further in section 2.3.1 below.

2.2.3 Summary

The study report [2] considers a range of optical architectures for distributing the microwave signal to or from a phased array antenna, including hybrid optical / microwave designs and those using wavelength division multiplexing (WDM) techniques. The architectures most likely to offer an advantage to the communications systems under consideration were identified for more detailed link analysis. In general the most significant advantage of using optical links in these applications was to remote the distribution and beamforming hardware away from the antenna panel into the central unit. The results of applying these architectures to the actual system requirements are summarized in section 2.4.

2.3 Architectures for Beamforming

The two principal types of beamforming control for an active phased array antenna are true-time delay (TTD) and phase steered. Both of these techniques can be realized in the optical domain, and their relative advantages and disadvantages are summarized in table 2.3.

True-Time Delay Beamforming	Phase Shift Beamforming
Frequency independent beam pointing.	Frequency dependent beam-pointing.
Large, complex equipment required.	Simple, small, integrated components
Suitable for large, wide-bandwidth, multi-frequency systems.	Suitable for small, narrow-bandwidth systems.
Optical Techniques Offer	**Optical Techniques Offer**
Fiber as a very wide-bandwidth time-delay medium	Integrated phase and amplitude control functions.
Smaller, lower mass TTD elements	Small, low power consumption beamformer.
	Frequency independent phase shift.

Table 2.3: Comparison of TTD and Phase shift beamforming approaches

Due to its large size and complexity, it is generally advisable to avoid using a TTD approach unless absolutely necessary. TTD tends to be adopted in systems where the effect of beam-squint at large scan angles seriously degrades the gain of the antenna. As a rule of thumb TTD only needs to be considered when:

$$\Delta B \; > \; \frac{f_0.\Delta\emptyset}{\emptyset_{max}} \qquad\qquad (2.1)$$

where ΔB is the instantaneous microwave bandwidth, f_0 the center microwave frequency, $\Delta\emptyset$ the antenna boresight beamwidth and $\emptyset_{max}$ the maximum scan angle from boresight.

TTD is unnecessary for all four systems summarized in table 2.1, therefore only optical phase steered techniques are considered in this report. Optical TTD techniques are, however, described in the study report [2].

2.3.1 Coherent Optical Beamforming

One method of realizing the necessary phase control of a microwave signal in the optical domain is to use coherent optical beamforming. This approach was developed independently by GMMT in the UK [7] and Soref et al. in the USA [15] and the concept was subsequently proven by GMMT in an

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experimental demonstration system developed for the European Space Agency [8]. Figure 2.3 illustrates the basic design as applied to the transmit link of a phased array antenna.

Coherent optical beamforming is based on a heterodyne process, whereby the microwave signal is generated at the photodetector by beating together two optical signals. The phase control is achieved by transmitting these two optical signals separately through an optical network such that a differential optical phase shift can be applied between them. In this way beamforming control is performed in the optical domain and hence the beamformer has the potential for being much smaller and to consume less power than an equivalent microwave unit.

Within the beamformer it is essential to maintain a high optical phase stability. This is achieved by keeping all optical path lengths as short as possible and propagating the two optical signals along a common waveguide so that they experience a common environment. In order to maintain their separate identity the signals are propagated in orthogonal polarization states. To realize this design the birefringence of the waveguide must be a compromise between a high value for low cross-coupling and a low value for thermal phase stability.

Using such a design, the optical distribution and beamforming functions can be integrated into a single, birefringent, electro-optic waveguide device containing polarization independent optical splitters followed by differential polarization electro-optic phase shifters and optical amplitude controllers. This produces a very compact, low power consumption unit.
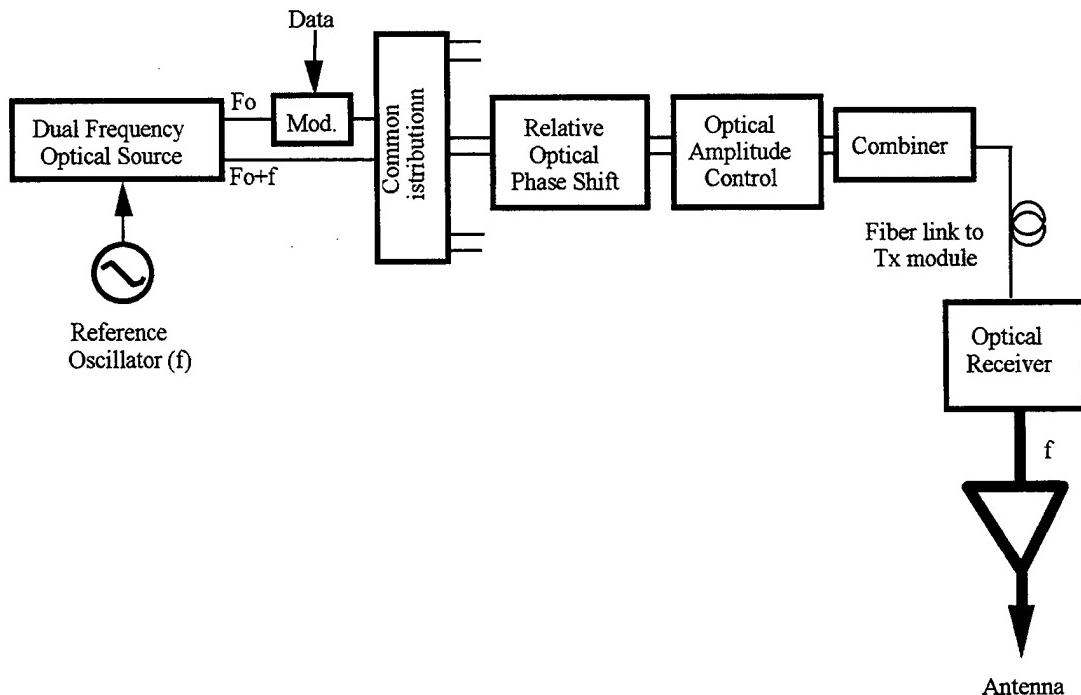
Fig. 2.3: Schematic of a transmit link coherent optical beamformer

In a communications transmit antenna it is necessary to modulate the microwave signal with the data in amplitude, phase or frequency. In a coherent optical beamforming link this could be performed in the optical domain as illustrated in figure 2.3, thereby removing the need for use of a modulated microwave input signal.

This design places stringent demands on the heterodyne optical transmitter, which has to produce two phase- and frequency-locked optical signals in orthogonal polarization states. Of the many techniques being investigated for microwave heterodyne transmitters only a few are suitable for this application, these include optical phase locked loop transmitters and single sideband optical modulators.

An optical phase locked loop (OPLL) transmitter is considered the most appropriate and flexible design for the transmit link. It consists of two narrow linewidth lasers which are frequency and phase locked to a reference microwave signal, thereby producing an efficient heterodyne signal whose

operating frequency range is determined by the microwave reference signal. Previous system demonstrations have employed diode-pumped Nd:YAG lasers (e.g. [8]) whose intrinsically narrow linewidths enabled an RF beat note to be achieved with a linewidth of less than 0.015 Hz. GMMT are currently assembling an OPLL device for CECOM for use at SHF based on two DFB lasers [9]. The RF beat note produced by such a device is predicted to have a close-to-carrier phase noise adequate for transmitting phase modulated data at data rates from less than 1 Mbit/s to more than 1 Gbit/s.

Single-sideband (SSB) optical modulators are required in an optical phase steered receive link, and may also be needed in transmit links with low data rates or when WDM approaches are adopted. The main advantage of the SSB modulator is that it is a linear device which will respond to the phase, frequency and amplitude of the input RF signal. Such a functionality is required in the receive link of a coherent optical beamforming system since the signals arriving at each antenna element could contain many frequencies with differing amplitudes and phases. The effect of the subsequent beamforming is to produce a combined signal, from all antenna elements, for those signals arriving from the direction defined by the beamformer.

GMMT have developed a practical SSB optical modulator [10] which operates at microwave frequencies and provides the carrier and sideband optical signals in orthogonal polarization states, as required for coherent optical beamforming. A 9 GHz version of this device has been provided to CECOM as part of the demonstration equipment [5].

2.3.2 Parallel Optical Beamforming

An alternative optically controlled phase steered antenna concept relies on bulk optics to perform the full two dimensional beam control. In its simplest implementation, a single optical source illuminates an array of optical controllers, such as a liquid crystal spatial light modulator, which match the antenna array pattern. The desired beam pattern can be programmed in the optical domain by the spatial light modulators and transferred to the antenna elements by imaging onto a matched array of photodiodes along with an LO optical source in order to down convert the signal to the microwave domain.

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This approach has the potential advantage of being very compact and it is conceptually simple to generate any desired beam profile. However, implementing such an approach in a practical system introduces serious problems with maintaining the beamforming optical path length stable to a fraction of a wavelength. The mass and thermal control requirements needed to realize a suitable support structure tend to obviate any gain derived from the parallelism of the optical processing. It was therefore concluded that this is not presently a practical approach for the systems under consideration in this study.

Summary
This section has introduced the basic concept of coherent optical beamforming; in the study report [2] a range of optical architectures based on this approach have been considered. The architecture most likely to offer an advantage to the systems in this study is one with the optical beamformer remote from the antenna. An optical beamformer is expected to be smaller, have lower mass and drive power requirements than an equivalent microwave one. Alternative architectures based on an optical beamformer manifold within the antenna unit should therefore not be ignored. The results of applying these architectures to the actual system requirements are summarized in section 2.4.

2.4   Proposed Architectures
The use of optical links in a phased array antenna has several potential benefits, those which have been used in the system analysis to identify the optimum design being:

- Reduced overall mass and power of system.
- Removal of significant, mass and power from antenna unit and simplification of the R/T modules.
- Modular design based on common link modules.

2.4.1 Mass and Power

The mass and power distribution has been predicted for each of the possible architectures as applied to each antenna requirement. In all cases the predictions were based on the use of optical components, integration and packaging techniques expected to be available within the next few years. Higher levels of optical integration are likely to reduce some of the size and mass predictions even further.

Modified RAP

Table 2.4 summarizes the mass and power distribution predicted when applying the various architecture designs to the 'Modified RAP' system. This analysis does not include components that are common to all systems, such as the antenna elements, the antenna housing, the transmit / receive modems and the beamforming computer.

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DESIGN	DESCRIPTION	CENTRAL UNIT		CABLE	ANTENNA UNIT		TOTAL	
		Mass (kg)	Power (kW)	Mass (kg)	Mass (kg)	Power (kW)	Mass (kg)	Power (kW)
μwave TX	μwave BF in antenna	3.4	0.042	5.2	40.1	0.54	48.6	0.58
Opt TX 1	optical remoting of μwave BF	53.3	2.0	14.3	18.4	0.39	86.1	2.4
Opt TX 2A	optical remoting of opto BF	12.4	0.093	14.3	20.5	0.41	47.2	0.50
" 2B	high power opt. post amp.	17.2	0.29	14.3	20.5	0.41	52.0	0.70
" 2C	med. power opt. boast amps.	10.9	0.07	14.3	20.5	0.41	45.7	0.48
" 2D	low noise opt. pre-amps	11.8	1.0	14.3	19.5	0.40	45.6	1.44
Opt TX 3A	optical BF in antenna	2.6	0.093	0.35	28.7	0.41	31.7	0.50
" 3C	med. power opt. boast amps.	1.0	0.013	0.35	28.9	0.47	30.2	0.48
" 3D	low noise opt. pre-amps .	1.0	0.013	0.35	29.7	1.43	31.1	1.44
Opt TX 4	hybrid opto/μwave splitting.	19.6	0.19	1.8	21.1	0.41	42.5	0.60

μwave RX	μwave BF in antenna	0.74	0.001	1.5	36.8	0.23	39.0	0.23
Opt RX 1	optical remoting of μwave BF	25.5	0.10	14.3	22.5	0.54	62.3	0.65
Opt RX 2	opto BF in antenna (1)	3.5	0.13	3.3	34.4	0.14	41.2	0.27
Opt RX 3	hybrid opto/μwave combining	1.8	0.007	1.1	36.4	0.28	39.3	0.35
Opt RX 4	opto BF in antenna (2)	16.3	0.13	14.6	27.8	0.14	58.7	0.27

Table 2.4:   Mass and power summary for the Modified RAP link designs

Table 2.4 includes a brief description of each architecture, more detail being available in the study report. The two optical beamforming transmit links (Opt TX 2 and Opt TX 3) have several variants depending on where in the optical link the optical amplification occurs. For comparison the table also includes the results for a conventional all-microwave link based on a microwave manifold with beamforming within the T/R modules.

For the transmit link the use of optical beamforming can reduce the overall mass and power consumption compared to an all-microwave design and also reduce the mass and power of the antenna unit. In either design option the use of booster amplifiers integrated within the optical

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distribution network provides the optimum design. In the case of the receive link, the need to achieve a low noise figure and high dynamic range requires high optical powers. A significant result of this is that while optical remoting and optical beamforming designs reduce the antenna mass and power, no design provides an overall mass and power advantage.

Link architectures 'Opt TX 2C' and 'Opt RX 2' are considered to be the best compromise designs for the 'Modified RAP' system in terms of mass and power distribution. Figure 2.4 illustrates a complete optical link design for the Modified RAP system. This design includes the use of 1-to-4 optical splitters (or switches) to drive the four antenna panels, plus a simple WDM to combine the signals for the two beams onto a common fiber cable.
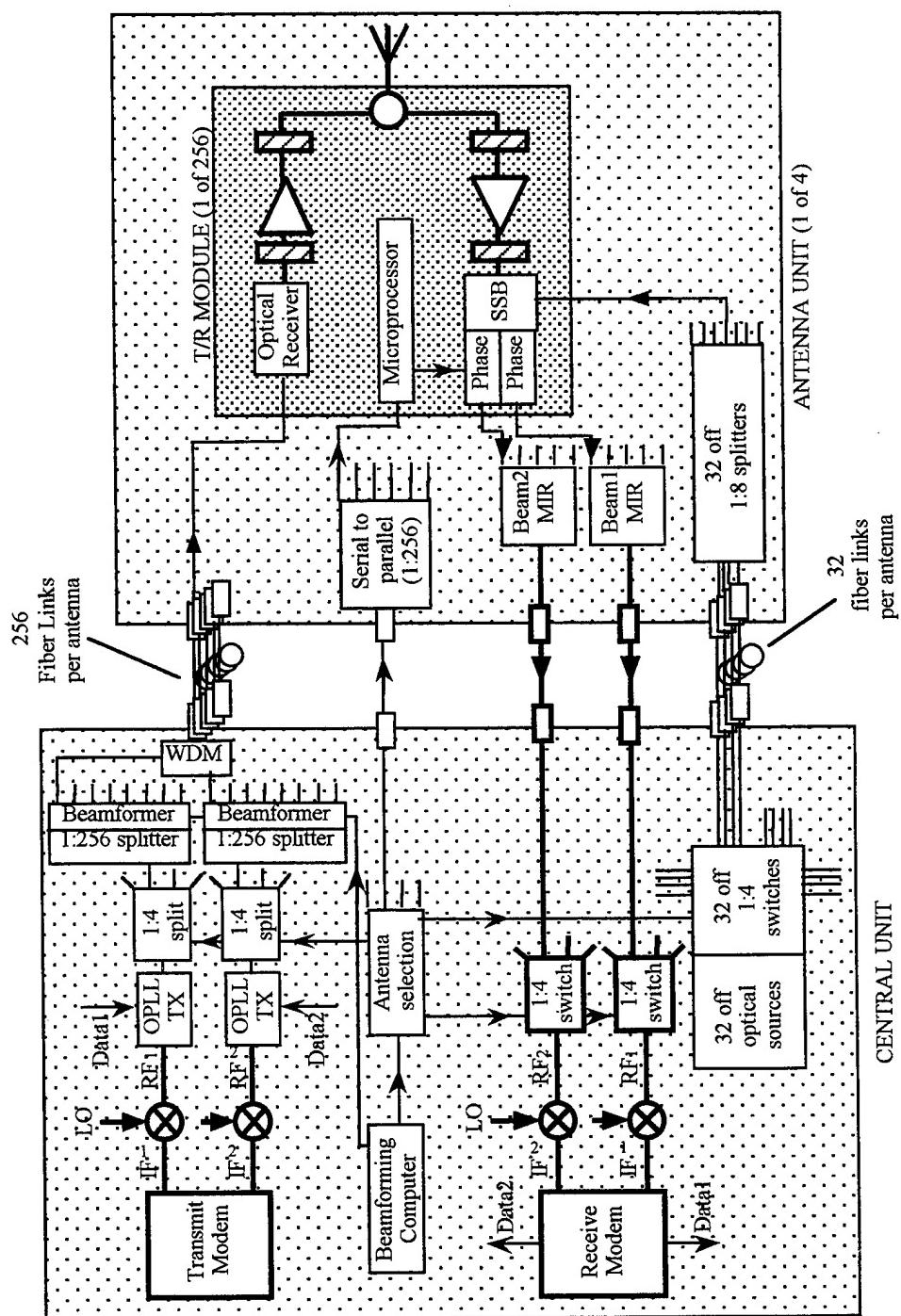
Fig. 2.4: Proposed optical link for Modified RAP system

Effect of Varying System Parameters

The optimum optical link design is likely to differ for differing system applications. To illustrate the effect of changes in the requirement, the link design of figure 2.4 has been applied to systems which differ in only one parameter from that of the 'Modified RAP'. The resulting mass and power summary is given in table 2.5, the changed parameters being typical of the different systems studied in this program.

	MICROWAVE LINK		OPTICAL LINK (TX 2C & RX 2)	
	Mass (kg)	Power (kW)	Mass (kg)	Power (kW)
Modified RAP	**87.1 kg**	**0.81 kW**	**86.3 kg**	**0.75 kW**
Increase transmitted power (10 W)	99.4 kg	3.7 kW	98.6 kg	3.7 kW
Increase number elements (2560)	772 kg	7.8 kW	787 kg	7.4 kW
Change data format (16-QAM)	97.4 kg	2.3 kW	98.7 kg	2.2 kW
Increase NF of receive link (11 dB)	87.1 kg	0.81 kW	84.2 kg	0.69 kW
Reduce NF (5 dB)	87.1 kg	0.81 kW	99.0 kg	1.13 kW
Reduce SFDR (50 dB)	87.1 kg	0.80 kW	82.2 kg	0.65 kW
Increase SFDR (70 dB)	92.2 kg	0.88 kW	98.6 kg	2.7 kW
Increase number of beams (3)	119 kg	1.1 kW	98.9 kg	0.91 kW
Increase number of panels (5)	108 kg	1.0 kW	108 kg	0.90 kW
Increase number of channels (2)	87.1 kg	0.81 kW	86.9 kg	0.76 kW
Amplitude and phase control	95.3 kg	1.2 kW	86.3 kg	0.75 kW

Table 2.5: Effect on mass and power of changing the specification of the modified RAP system. Each row of the table shows the effect of changing a single parameter in the 'Modified RAP' specification.

Compared to the conventional microwave link, a similar mass and power saving is maintained in systems which require a higher drive power, a larger number of elements, more panels or more channels. If the noise figure and (or) the linearity requirements are relaxed or additional beams are

required, the advantages of the optical link improve further. If, however, the NF requirement is smaller or the SFDR increases then the optical design becomes less favorable. Similarly if the data format is not an angle modulation (PSK or FSK) then the optical link advantage will be reduced slightly.

EHF RAP

The performance of the EHF RAP system differs from that of the Modified RAP in a number of parameters, such as higher transmit power, higher SFDR and more beams. The results in table 2.5 suggest that a link design similar to that proposed for the Modified RAP should have a similar mass and power advantage. However, the higher frequency of the EHF system (55 GHz) has a major impact on the choice of design due to the smaller element spacing (3.4 mm). This makes minimizing the amount of hardware in the antenna module the most important factor. Opt TX 2C design is considered to be the most suitable for the transmit link since this remotes the distribution and beamforming to the central unit. For the receive link Opt RX1 has been selected since this also remotes the bulk of the hardware to the central unit, but has the beamforming and combining functions in the microwave domain.

Tables 2.6 and 2.7 compare the mass and power distributions of an all-microwave EHF design with the proposed optical approach. As expected the mass and power of the antenna unit is significantly reduced in the optical remoting designs, but the overall mass is higher, this is due mainly to the large number of optical fiber links. The use of an optical link also reduces the overall power requirement, as a consequence of the high loss of any millimeter wave cable or waveguide used in the microwave links. One other very important factor to be considered is that the all-microwave design is unlikely to be a practical alternative at EHF due to the need to fit several beamformers and their associated control lines within each small T/R module.

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		μwave TX	μwave RX	TOTAL
Central Unit:	Mass (kg)	4.6 kg	0.66 kg	5.2 kg
	Power (kW)	0.012 kW	0.0003 kW	0.01 kW
Cables:	Mass (kg)	8.2 kg	1.9 kg	10.1 kg
Antenna Unit:	Mass (kg)	58.0 kg	66.3 kg	124 kg
	Power (kW)	0.89 kW	64.8 kW	66 kW
TOTAL:	**Mass (kg)**	**70.8 kg**	**68.9 kg**	**140 kg**
	Power (kW)	**0.90 kW**	**64.8 kW**	**66 kW**

Table 2.6:   Approximate mass and power of microwave EHF links

		Opt TX 2C	Opt RX 1	TOTAL
Central Unit:	Mass (kg)	13.3 kg	53.1 kg	66.3 kg
	Power (kW)	0.10 kW	1.4 kW	1.5 kW
Cables:	Mass (kg)	14.3 kg	14.3 kg	28.7 kg
Antenna Unit:	Mass (kg)	20.5 kg	34.8 kg	55.3 kg
	Power (kW)	0.63 kW	3.3 kW	3.9 kW
TOTAL:	**Mass (kg)**	**48.1 kg**	**102 kg**	**150 kg**
	Power (kW)	**0.74 kW**	**4.7 kW**	**5.4 kW**

Table 2.7:   Approximate mass and power of optical EHF links

SATCOM

Tables 2.8 and 2.9 summarize the approximate mass and power requirements for the SATCOM system, comparing an optical approach with a more conventional microwave one. This system requires separate transmit and receive antennas operating at 44 GHz and 22 GHz respectively. Sufficient room therefore exists within the Rx module to adopt the same optical beamforming approach used in the 'Modified RAP' system. The most critical difference with respect to the other systems is a factor of ten increase in the number of antenna elements. A moderately high level of wavelength multiplexing has been assumed to maintain a comparable number of fibers in the antenna link. In addition the system uses a low data rate FM link whose performance would be significantly

degraded by close-to-carrier phase noise of an OPLL-based link. A lower noise, but lower efficiency optical heterodyne transmitter has therefore been assumed, based on an external SSB modulator.

		μwave TX	μwave RX	TOTAL
Central Unit:	Mass (kg)	0.63 kg	0.003 kg	**0.7 kg**
	Power (kW)	0.004 kW	0.0 kW	**0.004 kW**
Cables:	Mass (kg)	0.72 kg	0.16 kg	**0.9 kg**
Antenna Unit:	Mass (kg)	59.4 kg	47.2 kg	**106 kg**
	Power (kW)	1.4 kW	0.25 kW	**1.7 kW**
TOTAL:	**Mass (kg)**	**60.7 kg**	**47.2 kg**	**108 kg**
	Power (kW)	**1.4 kW**	**0.25 kW**	**1.7 kW**

Table 2.8: Approximate mass and power of microwave SATCOM links

		Opt TX 2C	Opt RX 2	TOTAL
Central Unit:	Mass (kg)	16.0 kg	6.0 kg	**21.9 kg**
	Power (kW)	0.22 kW	0.26 kW	**0.48 kW**
Cables:	Mass (kg)	3.6 kg	3.8 kg	**7.4 kg**
Antenna Unit:	Mass (kg)	37.0 kg	51.1 kg	**88.1 kg**
	Power (kW)	1.3 kW	0.11 kW	**1.4 kW**
TOTAL:	**Mass (kg)**	**56.5 kg**	**60.8 kg**	**117 kg**
	Power (kW)	**1.5 kW**	**0.37 kW**	**1.9 kW**

Table 2.9: Approximate mass and power of optical SATCOM links

The mass of the transmit antenna is significantly reduced in the optical approach, mainly through using optical remoting. There is also a small reduction in the antenna power. The optical receive antenna is, however, heavier than its electrical equivalent but requires slightly less drive power. In the central unit the combined mass and drive power of the optical system is significantly greater than the microwave version. This is due mainly to the large number of high power optical sources needed for the receive link to achieve the required SFDR and NF.

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We conclude for the SATCOM system that, in terms of mass and power only, an optical beamforming transmit link is a good design option, provided WDM technology is employed. For the receive link, however, neither approach produces an overall advantage. Other parameters such as the space constraint of the T/R module and environmental effects have therefore been considered in determining the optimum receive link design.

2.4.2 Modular Link Design

In all of the optical link designs the possibility of adopting a modular approach to the optical functions was considered. Such a design can be very flexible, enabling the system to be readily expanded (e.g., more elements or more beams), and the frequency independence of the optical beamforming units allows for common usage of some modules for a wide range of system applications.

Transmit Link

The proposed coherent optical beamforming transmit link has been divided into four basic optoelectronic modules, as illustrated in figure 2.5. The following paragraphs briefly discuss each module in terms of its design and suitability for multiple applications.
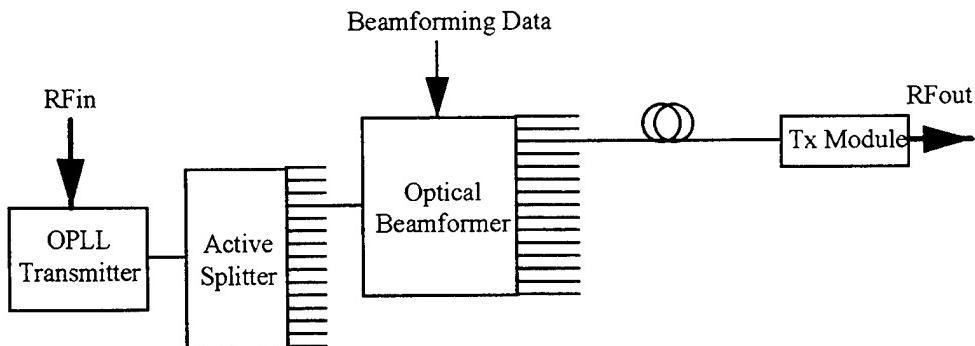
Fig. 2.5: Modules required for the transmit optical beamforming link Opt TX 2C.

Dual Frequency Transmitter

The main function of this module is to provide the two phase locked, orthogonally polarized optical signals and also to enable any data modulation to be imparted onto them. Such a device is therefore very specific to each application.

For the Modified RAP design it is possible to use the efficient OPLL design with an external electro-optic phase modulator for QPSK data modulation. The transmitter for the EHF RAP system will be essentially the same, except the feedback loop of the OPLL must operate at 55 GHz. Several components, such as the laser diodes, polarization optics and optical data modulator, will be identical for both systems, therefore it should be possible to adopt a common internal design where only the feedback circuit needs to be replaced for each center frequency.

For the SATCOM system a single side-band (SSB) optical modulator, driven by the data encoded microwave signal, is preferred due to the wavelength multiplexing design and the requirement for a low data rate frequency modulation format.

Optical Beamforming Unit

This unit is made up from a combination of active splitter and splitter / beamformer modules, the number of each being dependent on the size of the array. Table 2.10 illustrates the number of each module type required for a range of antenna sizes, assuming a maximum sixteen-way split for both the active splitter and splitter / beamformer modules.

Module \ No. Elements	16	64	256	~2000
Active Splitter (1-to-16)	0	1	1	9
Optical Beamformer (1-to-16)	1	4	16	128

Table 2.10: Active splitter and beamformer modules required for different size antennas

The modular nature of the active splitter and splitter / beamformer therefore produces flexibility in the antenna size and, being all-optical, these modules are suitable for use in systems with any carrier frequency.

Tx Module

In its simplest form this module contains a photo-receiver, to convert the incoming modulated optical signal into a microwave one, followed by a chain of amplifiers and finally the antenna power amplifier. If a full duplex, common antenna system is used this module must also contain filtering and isolation to minimize the effect of crosstalk in the receive path. Such a module is specific to its design frequency band and power output, but provides for some flexibility in that higher antenna gains can be achieved by increasing the number of modules in an antenna (i.e., more elements).

The same Tx module can also, in principle, be used for any number of independent transmit beams. Multi-beam transmit operation is most simply achieved by using wavelength multiplexing to send the modulated optical signal for each beam along the same fiber, thereby using the same detection and amplification chain in the Tx module as a single beam. This approach is very compact, but results in the output power per module being shared between the beams and imposes a linearity constraint to minimize intermodulation effects.

Receive Links

The receive link designs of figures 2.6 and 2.7 illustrate the module requirements of the two architectures proposed in the previous section.
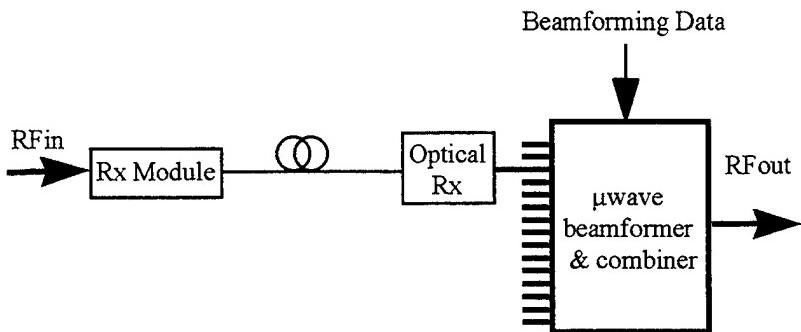
Fig. 2.6: Modules required for the receive optical beamforming link Opt RX 1.
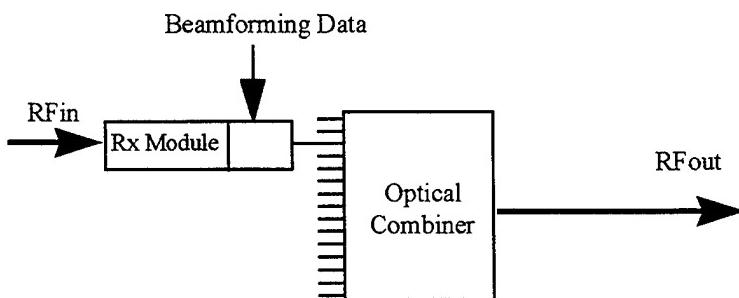
Fig. 2.7: Modules required for the receive optical beamforming link Opt RX 2.

Rx Module

There is very little difference in the design of the Rx antenna module for either the optical remoting link (Opt RX 1) or the optical beamformer link (Opt RX 2) system. Both require a chain of amplifiers after the LNA in order to drive an external optical modulator. The remoting design uses a DSB optical modulator whereas the optical beamforming approach requires an SSB device with integrated beamformer (phase and amplitude control). In both cases the optimum design assumes the optical power is remote from the module, therefore each modulator has both an input and output optical port. In the case of the optical beamformer design, data control lines are required from the beamforming computer. The SSB and DSB modulators can be made wideband, but the frequency range of the complete module will tend to be limited by the amplifiers and antenna in order to minimize the noise bandwidth.

Signal Combiner

In the optical remoting design the fibers from each Rx module are taken to the central unit where photo-receivers convert their modulated optical signals into microwave ones. The resulting beamforming and signal combining takes place in the microwave domain. It is possible to integrate some of these components to minimize the size (e.g., photodetector arrays), but the overall function will tend to be frequency-dependent, and therefore is not suitable for all applications.

In the adopted optical beamforming system the photo-receivers and signal summation takes place as close as possible to the Rx module in order to minimize optical phase errors. An antenna summing manifold is therefore required. The multi-input receiver (MIR) unit which provides this function consists of a set of photodiode arrays each integrated with a common microwave transmission line, the microwave output of each one being combined and transmitted to the central unit. Such a device will tend to be frequency specific, although wideband designs capable of operating up to around 20 GHz have been demonstrated.

2.5 Active Components

The optical architecture designs for the systems described in the previous section were based on assumed performance values for various optoelectronic components. Wherever possible these values were based on recently reported and achieved device performance levels. The 'Technology Study' report [3] details the required component performance, discusses how the components could be realized in practice and describes techniques which could be used to assemble them into the low cost, high performance modules. Tables 2.11 and 2.12 provide a summary of this analysis for the transmit and receive optical link designs of the Modified RAP system (figure 2.4). In these tables the components are grouped into their modules, and the minimum value of the most critical performance requirements is given. The final two columns summarize the component type and assembly method which could be used to produce the required module performance based on either current technology or that expected to be available within the next few years.

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		CURRENT DESIGN	FUTURE DESIGN
OPLL TRANSMITTER:		Discrete assembly of optical and electrical components	Integrated assembly with an OEIC OPLL waveguide and MMIC feedback circuit
Ex-facet power of master laser	40 mW	Solid state laser or discrete high power DFB.	High power DFB, possibly integrated with OEIC.
Ex-facet power of slave laser	20 mW	Tunable solid state or semiconductor laser.	Tunable semiconductor laser integrated with OEIC.
FM efficiency of slave laser	5 GHz/mA	″	″
RIN of lasers	-150 dB/Hz	″	″
Combined laser linewidths	6 MHz	″	″
ACTIVE SPLITTER:		PM-EDFA followed by a silica waveguide 1:16 splitter.	OEIC with 1:16 MMI splitter and a high power SOA in each output.
Effective Gain (I/P fiber-to-O/P)	+2 dB	″	″
O/P 3 dB compression power	+10 dBm	″	″
SPLITTER / BEAMFORMER:		Fiber interfacing using Si v-groove arrays.	Hybrid integrated assembly with active splitter.
Fiber-to-fiber loss	28 dB	Custom electro-optic waveguide LiNbO$_3$ or GaAs	GaAs electro-optic waveguide
Max. control voltage	10 V	″	″
TX MODULE:		Separate packaged optical and microwave components	Hybrid opto and microwave assembly.
Responsivity of photodiode	0.7 A/W	″	″
Photo-receiver post-amp gain	20 dB	″	″
Gain of amplifier chain	60 dB	″	″
Compression power of drive amp	+15 dBm	″	″

Table 2.11: Modified RAP Tx link optoelectronic component requirements

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		CURRENT DESIGN	FUTURE DESIGN
RX MODULE:		Separate packaged optical and microwave components	Hybrid opto and microwave assembly.
Gain of LNA plus amp chain	40 dB	"	"
O/P TOI of LNA plus amp chain	+19 dBm	"	"
Optical loss of SSB / splitter	11 dB	GaAs EO external modulator design	EA or enhanced EO design.
Drive power for 10% conversion	+10 dBm	(not currently available)	"
Effective TOI drive power	+20 dBm	(not currently available)	"
Max. control voltage	10 V	GaAs EO external modulator design	"
OPTICAL COMBINER:		Discrete 16 channel MIRs with external microwave combiner	Hybrid integration of MIRs and microwave combiner.
Responsivity of each photodiode	0.7 A/W	"	"
Number of photodiodes per array	16	"	"
CW POWER SOURCE:		Solid state laser	Fiber laser or high power DFB
Power into SM fiber	40 mW	"	"
RIN of optical power source	-160 dB/Hz	"	"
1:8 distribution loss	13 dB	Fiber splitter	Fiber splitter

Table 2.12: Modified RAP Rx link optoelectronic component requirements

Of all of the component requirements listed in tables 2.11 and 2.12 only the modulation efficiency of the SSB modulators cannot be achieved with existing approaches, current devices being about 10 dB below the target requirement. However, alternative designs, such as devices based on parallel electro-absorption modulators [14] could possibly achieve the desired efficiency. The main design emphasis over the next few years is to develop the necessary packaging, interfacing and integration technologies, the majority of the component performance characteristics being already possible.

One critical integration area is to develop an integrated active splitter containing a multi-way MMI splitter with optical amplification on each output. The most likely design is based on an InP OEIC with semiconductor optical amplifiers, although devices based on doped waveguide amplifiers may become practical in the near future.

In the area of packaging it is essential to develop a practical, low cost, rugged and reliable approach for optical interfacing to a multi-waveguide device, possibly based on a passive or semi-passive design.

In the T/R modules significant space reduction could be realized if a common optical microwave assembly substrate is adopted. Monolithic integration could be used to minimize the component size and to avoid several difficult interfaces. However, the technology is so far insufficiently mature to achieve the desired performance or yield in all but the simplest of devices, and in many cases a hybrid assembly can be more flexible than a fully integrated design.

2.6   Interconnection Technology

The passive optical functions and components within an optically fed phased array antenna system are the optical splitting, optical interconnection, the optical cable to the antenna and an optical backplane within the antenna unit. In the case of an optical beamforming system it is considered preferable to adopt a modular design in which the passive splitting functions are integrated with the active components such as optical amplifiers and electro-optic beamformers. For this reason the optical splitting components have been discussed in the previous section.

The optimum Modified RAP designs require at last 256 fibers in the cable linking the beamformer to each antenna (one per element) for both transmit and receive links. The transmit link relies on the optical fiber having a good microwave phase stability with temperature, which in turn requires the use of single-mode, silica fiber rather than the cheaper but less stable alternatives such as multi-mode or polymer fibers. Single-mode ribbon fiber technology suitable for the multi-way interconnection has

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been developed, with up to 12 fibers per ribbon being used currently, and at least 16 fibers is expected to be available soon. The size limitation is set by the availability of multi-way connectors. A practical 256 fiber cable could consist of sixteen 16-fiber ribbons in a common outer sheathing, or alternatively sixteen separately sheathed 16-fiber ribbons. The common cable approach would help to minimize temperature differentials between the fibers, but separate cables are more flexible and compatible with the modular design approach.

The optical connection between the fiber cable and the antenna unit is a critical design issue since it impacts the antenna size. A system is unlikely to use a simple single-mode connector to each T/R module, due to the smallest single fiber connectors being as much as 8 mm in diameter. If, however, the T/R modules are combined, for example, into 'quadpacks', the required eight fibers (4 Tx, 4 Rx) could be accommodated in a single multi-termination connector which is only 12.6 mm wide. A more general approach would be to use an optical backplane to provide an optical pathway from multi-way fiber connectors at the edge of the complete antenna unit to each T/R module. Such an optical backplane could be based on large polymer waveguides or a flexible board containing embedded optical fibers.

2.7   Preliminary Environmental Analysis

The RAP antenna is to be fixed onto an army vehicle (HMMWV), where the environment will be less severe than the avionic applications for which GMMT have previously designed and assembled optoelectronic modules. As no detailed environmental specification was provided, the values listed in table 2.13 were assumed. The actual environment of the HMMWV will probably be less severe, particularly the vibration which is unlikely to be as large as $0.1g^2/Hz$ or to contain components at frequencies as high as 2 kHz.

Temperature	-40°C to +55°C (operational)
Vibration	< 0.1 g²/Hz (10 - 2000 Hz)
Radiation	< 1 Gy

Table 2.13: Assumed worst case Modified RAP environment

The technology study report [3] discusses the impact of environmental factors on the performance of optoelectronic components and packages. These results have been applied to the optically fed Modified RAP system and used to perform a preliminary environmental sensitivity analysis. The effect of the assumed radiation level is very small, producing less than 0.01 dB of excess loss in the optical fiber links. The analysis therefore considers only temperature and vibration effects, the results of which are summarized in table 2.14. This analysis considers only environmental induced performance changes; other factors such as assembly tolerances or calibration errors must also be considered when analyzing performance changes in a complete system.

		TEMPERATURE [-40°C to +55°C]	VIBRATION [0.1 g²/Hz (10 - 2000 Hz)]
TX Link:	Gain	-2.8 dB to +0.8 dB	±1.3 dB
	RMS. amplitude	0.7 dB	0.4 dB
	RMS. phase	10°	1.2°
RX Link:	Gain	±0.1 dB	0.1 dB
	RMS. amplitude	0.2 dB	<0.1 dB
	RMS. phase	1.4°	<0.1°

Table 2.14: Predicted environmental sensitivity of Modified RAP system

The largest contributions to the temperature-dependent gain variation of the transmit link are movements at optical interfaces in the OPLL and active splitter modules. These modules are positioned within the central unit where larger, more robust packaging could be used to minimize temperature induced movements. A feedback technique, controlling either the gain of the SOAs or

the power of the OPLL lasers, could also be employed if necessary, with unused output ports of the beamformer unit being used for the power monitoring.

The predicted RMS phase and amplitude errors are just tolerable for the target sidelobe requirement of -15 dB, but leave little margin for additional effects such as assembly tolerances, calibration errors and performance changes with time. The dominant contributions to the phase change are temperature induced optical effects in the optical fibers and the SOAs. Slow phase changes within the PM fiber and SOAs in the beamformer unit could be actively compensated by the use of additional phase control elements at the input of each splitter / beamformer module. Temperature induced effects in the fibers linking the beamformer to the antenna modules can be minimized by careful length matching and close packing of the fibers within the cable.

2.8   Conclusion

In conclusion, the architecture study identified optical remoting, distribution and coherent optical beamforming as beneficial approaches to the specified phased array antennas for communications on-the-move. Slightly different designs were required for the alternative systems studied. The small size of the EHF RAP T/R modules necessitated the use of optical remoting in both transmit and receive, whilst the large number of antenna elements in the SATCOM system benefited from using wavelength multiplexing to minimize the number of interconnecting fibers.

Analyzing the selected optical designs it was possible to make the following conclusions:

- RAP system: Reduces mass (23%) in the antenna.
- Modified RAP: Reduces mass (29%) and power (28%) in the antenna.

    Reduces mass (1%) and power (8%) of the complete system.
- EHF RAP: Reduces mass (54%), power (13%) and complexity of the antenna.

    Optical remoting makes small T/R modules possible.
- SATCOM: Reduces mass (17%) and power (18%) in the antenna.

    WDM minimizes mass and complexity of interface cable.

    Optical remoting makes small Tx modules possible.

The technology study demonstrated that most of the optoelectronic components with the required performance have already been realized, the most important exception being the active splitter and a high efficiency SSB modulator. Apart from these devices, where improved performance is required, the main developments required are in the areas of packaging, interfacing and integration such that a rugged high performance system can be assembled at reasonable cost.

3. EXPERIMENTAL DEMONSTRATOR

The second phase of the program was to design, build and deliver an experimental demonstrator capable of achieving the basic link functions of the proposed optical beamforming system. The work summarized in this chapter is contained within three technical reports. The 'Design Plan' [4] outlines the functions and target performances of the proposed modules and the demonstrator system. This design was approved by CECOM before proceeding with the actual build. The 'Design and Build of Demonstration Equipment' report [5] describes, in detail, each of the modules within the delivered demonstration system. This includes the design of the basic semiconductor optoelectronic devices, their fabrication, packaging, final module assembly and testing. The 'Operation Manual for Demonstration Equipment' [6] was delivered with the equipment and describes, in outline, the basic operation of each module, how they interface in the complete system and their performance as measured prior to shipping.

3.1 Design of Experimental System

It was proposed to build and deliver a set of optoelectronic component modules which would enable the basic link functions to be implemented and assessed, as a prelude to the design and build of a complete array demonstration in a subsequent project. In order to realize a useful demonstrator within the limited scope of this program the design was based around the following criteria:

- The equipment needed to be built and tested within the timescales and funding constraints of the project.
- Critical modules should be fabricated so that both a transmit and receive link can be investigated and these are to be compatible with a four element antenna array.
- The performance of the modules should enable the experimental demonstrator to approach critical aspects of the RAP link specifications.
- The equipment could be readily upgraded and extended, if required, to investigate other RAP functions, e.g., multi-beam or multi-antenna operation.

- The demonstrator modules should be compatible with optoelectronic components and equipment being fabricated under other CECOM funded projects.
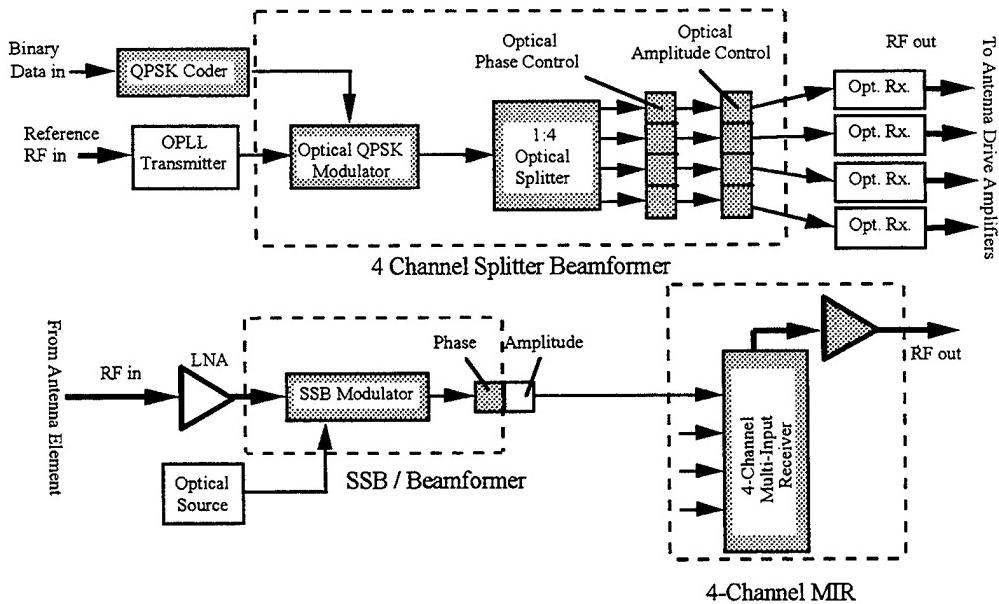
Fig. 3.1: Proposed Tx and Rx functional modules of demonstration equipment

Figure 3.1 illustrates the design for the basic transmit and receive link demonstration. The shaded functions represent those supplied by GMMT and the dashed outlines illustrate the four basic modules: QPSK coder, splitter / beamformer, SSB modulator / beamformer and multi-input receiver (MIR). The other, more readily available functions such as the optical sources, coherent optical transmitter and single-input optical receivers are to be supplied by CECOM for the experimental system evaluations.

It was proposed to build the four GMMT modules on 'Eurocard' boards which plug directly into a 3U high 19" sub-rack containing a common power supply. The final layout of this equipment rack is shown in figure 3.2, which also illustrates the optical, electrical and RF front panel connections.

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EC50		OPTICAL OUTPUT	DATA CLOCK	IP. MONITOR	RF IN

Figure panel layout:

- **EC50** — (o)
- **POWER ON/OFF**
- **SPLITTER / BEAMFORMER**:
  - OPTICAL OUTPUT 1 2 3 4 (O O O O)
  - OPT. IN DATA IN O I — O OI OQ MON. OQ
  - AMPLITUDE CONTROL 1 2 3 4 (o o o o)
  - PHASE CONTROL 1 2 3 4 (o o o o)
- **QPSK CODER**:
  - DATA CLOCK (O O)
  - I OUT Q OUT (O O)
  - I MON. Q MON. (O O)
- **MULTI-INPUT RX.**:
  - IP. MONITOR (● ●)
  - OPTICAL INPUTS 1 2 (O O)
  - 3 4 (O O)
  - RF OUT (O)
- **SSB MODULATOR**:
  - RF IN (O)
  - OPTICAL IN (O)
  - OPTICAL OUT (O)
  - PH. SHIFT (o o)

Fig. 3.2: Layout of demonstration equipment showing front panel connections

3.1.1 Transmit Link

The demonstrator transmit link illustrated in figure 3.1 is divided into three optoelectronic modules and one electrical one. The OPLL transmitter and the optical receiver modules were provided by CECOM, the remainder were fabricated by GMMT. The splitter / beamformer module contains the data modulator, a four way optical splitter and four phase and amplitude beamforming controllers. The QPSK coder is a digital interface which converts an ECL binary data signal into the appropriate format for driving the QPSK data modulator integrated within the splitter / beamformer module.

OPLL Transmitter

The initial equipment trials at CECOM will use a commercial OPLL transmitter unit from Lightwave Electronic inc., based on diode pumped Nd:YAG lasers operating at 1.3 μm. All of the optoelectronic components within the transmit link were therefore designed for optimum operation at this wavelength. A compatible OPLL transmitter based on semiconductor lasers is being fabricated at GMMT under a separate CECOM program [9]. The following table is a summary of the minimum performance assumed for the Nd:YAG OPLL transmitter.

Optical power in TM polarization state	10 mW
Optical power in TE polarization state	5 mW
Source RIN	-160 dB Hz
Polarization crosstalk	-20 dB
Beat frequency	9±2 GHz
Beat linewidth	3.5 kHz
Output fiber pigtail	PMF (Bow-tie or Panda)
Optical connector	PM keyed Super-PC

Table 3.1: Summary of assumed Nd:YAG OPLL transmitter performance

Splitter / Beamformer Module

The proposed design for the splitter / beamformer device was to integrate a 1-to-4 MMI splitter with four independent electro-optic phase and amplitude controllers. It was also proposed to integrate the QPSK optical data modulator onto the input waveguide. The preferred electro-optic waveguide medium for this integration was GaAs, since it is capable of achieving all of the desired functions in a relatively low loss, compact, stable waveguide medium.

Number of output channels		4
Fiber to fiber loss		21 dB
Polarization crosstalk		-20 dB
QPSK:	Voltage for π phase shift	10 V
Voltage for π/2 QPSK phase shift		10 V
Beamformer:	Voltage for π phase shift	15 V
Voltage for max. amplitude extinction		±30 V
Max. amplitude extinction (TE only)		10 dB
Optical Interface:	Optical input	PMF (Bow-tie or Panda)
Input optical connector		PM keyed Super-PC
Optical output		Polarizing Fiber (3M)
Output optical connectors		Super-PC
Electrical Interfaces:	Beamformer controls	Filtered feedthrough pins
'I' & 'Q' QPSK data inputs		SMA connectors

Table 3.2: Target performance of splitter / beamformer module

An electrical interface circuit is included in the final module assembly. This converts the ECL signals from the QPSK coder into the correct voltage levels to drive the optical QPSK phase modulators. Table 3.2 summarizes the target performance and panel interfaces for this module.

Optical Receiver Module

Operation of the full demonstrator transmit link requires four 9 GHz photo-receivers. As there are several commercial suppliers of such devices, it was not proposed to supply them as part of the experimental equipment. As an example, the following table summarizes the performance of a basic wideband, 18 GHz photo-receiver typical of the ones fabricated by GMMT.

Responsivity (1320 nm at 9 GHz)	0.6 A/W
Frequency 3 dB bandwidth	18 GHz
Pre-amp gain	10 dB
Equivalent thermal noise photocurrent	<15 pA/√Hz
Input 1 dB compression power of pre-amp	-10 dBm
Input optical connector	Super-PC

Table 3.3: Summary of assumed photo-receiver performance

In a practical phased array antenna system a custom photo-receiver design will be required in order to fit within the profile of the Tx module and also to provide a higher gain and lower noise.

Predicted Transmit Link Performance

The predicted performance of the demonstration transmit link given in table 3.4 assumes all of the fabricated, assembled and purchased equipment achieves the target performances summarized above.

LINK PERFORMANCE	
O/P noise power density	-159 dBm/Hz
O/P RF power (no attenuation in beamformer)	-25.4 dBm
O/P carrier to noise ratio (CNR)	133 dB Hz

Table 3.4: Predicted performance of demonstrator transmit link

3.1.2   Receive Link

The demonstrator receive link is divided into the three functional modules illustrated in figure 3.1. GMMT designed, fabricated and assembled the SSB modulator with integrated beamformer and the four channel multi-input receiver; the high power, low noise optical source was provided by CECOM. Four SSB modulator / beamformers are required for a complete four channel receive link. Supplying this number of units was not possible under the constraints of the program, however, the modular design means they can be readily added at a future date if required.

Optical Source Module

The full RAP system receive link (figure 2.4) requires several high power low noise optical sources to provide the optical power to each of the Rx antenna modules. To realize a similar performance in this laboratory demonstrator it was proposed to use a diode pumped Nd:YAG laser. Such a source is available at CECOM, and its use dictated that the optoelectronic components within the link were designed for optimum operation at 1.3 μm. The following table is a summary of the minimum performance assumed for the fibered Nd:YAG laser source.

Optical power in single polarization state	50 mW
Source RIN	-160 dB Hz
Polarization crosstalk	-20 dB
Output fiber pigtail	PMF (Bow-tie or Panda)
Optical connector	PM keyed Super-PC

Table 3.5: Summary of assumed Nd:YAG OPLL transmitter performance

Single Sideband Modulator and Beamformer Module

The SSB modulator is one of the more critical components in the receiver module, its performance being one of the limiting factors to achieving the overall link performance. The SSB modulator design was based on an existing GMMT approach, previously proven in GaAs waveguide technology [10]. The device also requires an optical beamformer to be integrated into the output waveguide of the modulator. Constraint on the current maximum chip length precluded the integration of both phase and amplitude control in the demonstration equipment. The target performance for the complete fibered unit is given in table 3.6:

Fiber to fiber loss (at optimum bias)		15 dB
SSB:	Center frequency	9±2 GHz
	3 dB bandwidth	2 GHz
	Drive power for 10% SB conversion	+30 dBm
	Carrier suppression	-20 dB
	Image sideband suppression	-20 dB
Beamformer:	Voltage for π phase shift	15 V
Optical Interface:	Optical input	PMF (Bow-tie or Panda)
	Input optical connector	PM keyed Super-PC
	Optical output	Polarizing Fiber (3M)
	Output optical connectors	Super-PC
Electrical Interfaces:	Beamformer controls	Filtered feedthrough pins
	RF drive	SMA connectors

Table 3.6: Target performance of SSB / beamformer module

Multi-Input Receiver Module

It was proposed to fabricate a four channel, 10 GHz multi-input receiver consisting of an array of four, isolated, substrate entry, closely spaced, InGaAs photodiodes flip-chip bonded to a coplanar microwave transmission line. Individual optical fibers would be coupled to each photodiode in the array.

Within the module assembly the microwave output of the MIR device would be coupled to a pre-amplifier to provide a useful signal level and to impedance match to any test equipment. The target performance and interfaces to this module are summarized in table 3.7.

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Photodiodes:	DC responsivity	0.7 A/W
	8 GHz responsivity	0.6 A/W
Amplifier:	Gain (@ 8 GHz)	15 dB
	Lower 3 dB bandwidth	6 GHz
	Upper 3 dB bandwidth	12 GHz
	Noise Figure	3 dB
	Output VSWR	2.0:1
Optical Interface:	Optical input	SM Fiber
	Input optical connector	Super-PC
Electrical Interfaces:	RF out	SMA connector
	DC power monitor	Feedthrough pins

Table 3.7: Target performance of MIR module

Predicted Receive Link Performance

The predicted performance of the demonstration transmit link given in table 3.8 assumes all of the fabricated, assembled and purchased equipment achieves the target performances summarized above. Note that this link performance does not include an LNA driving the SSB modulator and hence the link has a correspondingly low gain and high noise figure.

LINK PERFORMANCE	
Small signal link gain	-35.5 dB
Noise figure	59 dB
O/P RF power (0 dBm drive to SSB)	-35.5 dBm
O/P carrier to noise ratio (CNR)	115 dB Hz
Spurious free dynamic range (1 Hz bandwidth)	109 dB

Table 3.8: Predicted performance of demonstrator receive link

3.2 Design, Fabrication and Assessment of System Components

To achieve the module functionality and performance summarized in the previous section required the design, fabrication and packaging of the custom optoelectronic devices. This section summarizes the

design and performance achieved. Their assembly into the 'Eurocard' modules and subsequent testing is summarized in section 3.3.

3.2.1 Splitter / Beamformer

The integrated optical splitter / beamformer function is required as part of the transmit link and a large mass and size advantage can be gained by using monolithic integration to combine the optical beamforming functions (phase and amplitude control) with the optical distribution. It would be desirable to integrate as large a number of splitting elements as possible into a single waveguide, however, for this equipment a four-way distribution was considered adequate to demonstrate the technology.

Theory / Background

The integrated device required for the proposed coherent optical beamforming system must contain an optical splitter, a polarization dependent phase controller and an optical intensity controller. The latter two functions require the use of an electro-optic waveguide medium, such as $LiNbO_3$, GaAs or InP. The waveguide medium adopted for this application was GaAs due to its small size, environmental stability and potential for integration with active and electrical functions.

The critical performance of the optical splitter function is to provide low loss, uniform, stable, polarization-independent splitting of the light. It was decided to use a multi-mode interference (MMI) splitter design due its low loss, small size, low polarization dependence and relative intolerance to fabrication variations. Rib loaded waveguides in GaAs are particularly suited to the realization of an efficient multi-way MMI splitter due to their high mode volume.

The device requires two electro-optic functions, a differential polarization phase shifter and an optical intensity controller, to be integrated into each output waveguide. In a GaAs device the differential phase control occurs automatically since there is no electro-optic effect for TM polarized light. (Second order effects produce a TM phase shift which is less than 1% of the TE electro-optic effect.) Suitable electro-optic intensity control can be achieved using the same optical phase shift control

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within a Mach-Zehnder interferometer configuration. In a GaAs device, only the TE light will be attenuated under voltage control, therefore a 1 dB reduction in the microwave power at the Tx module will be achieved with a 1 dB attenuation of the TE optical power in the beamformer.

Device Design

In addition to the 1-to-4 splitter and optical beamforming elements it was agreed, for this particular demonstrator, to integrate optical phase modulators on the input waveguide to act as the QPSK data modulator.

In the design of the splitter / beamformer device several competing parameters had to be considered. In particular it was desirable to have the electrodes as long as possible, in order to increase their electro-optic efficiency, and space was needed to separate the waveguides at the MMI splitter output to a suitable fiber spacing at the device output. On the other hand a short chip was preferred in order to increase the number of devices from a single wafer fabrication. The following design was adopted as a good compromise based on the performance requirements, wafer size and current best practice for GaAs waveguide devices.

QPSK π electrode length	10 mm	(Predicted V_π = 10 V)
QPSK π/2 electrode length	5 mm	(Predicted V_π = 20 V)
Phase shifter electrodes (4 off)	6.6 mm	(Predicted V_π = 15 V)
Attenuator electrodes (4 off)	3.3 mm	(Predicted V_π = 30 V)
Length of 1-to-4 MMI region	650 μm	
Width of 1-to-4 MMI region	30 μm	
Waveguide separation at MMI O/P	7.8 μm	
Waveguide separation at chip O/P	160 μm	
Length of chip	32.5 mm	
No. of chips on 2" wafer	11	
Minimum waveguide bend radius	15 mm	
Approx. waveguide mode radius	2.2 x 1.6 μm	

Table 3.9: Design parameters of the 4-channel GaAs splitter / beamformer device

The modeling of the 1-to-4 MMI splitter gave an optimum length for TE polarized light as 630 μm whereas for TE it was 670 μm; a compromise length of 650 μm was therefore adopted.

Figure 3.3 illustrates the design of the splitter / beamformer GaAs waveguide chip. This is a composite plot of the various photo-lithographic mask layers and as such only the larger features such as the electrodes and DC bond pads are apparent. This device has two electrode sections on the input waveguide for the π and π/2 QPSK optical phase shifters, each of the four output waveguides having their own independent phase and amplitude control.
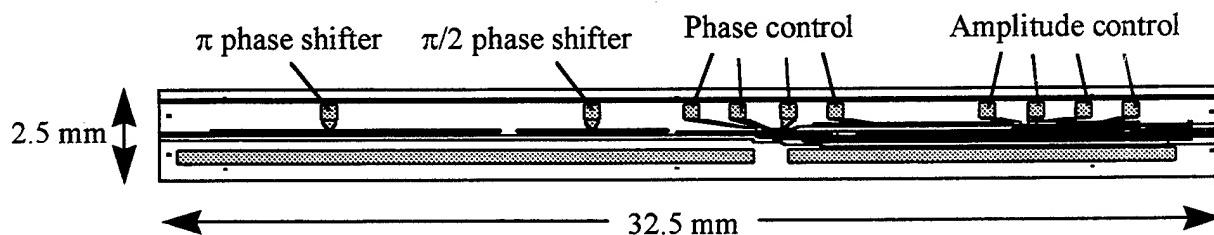

Fig. 3.3: Splitter / Beamformer Chip Design

Device Characterization

The following table summarizes the results of loss, extinction ratio and electro-optic measurements made on the waveguide chip used in the delivered splitter / beamformer module. These values are typical of all devices on the wafer.

Beamformer Chip	Measured			
	O/P 1	O/P 2	O/P 3	O/P 4
TE device loss	10.4 dB	12.0 dB	12.4 dB	12.4 dB
TM device loss	11.3 dB	13.4 dB	13.9 dB	13.9 dB
Max. optical attenuation (TE)	-9.7 dB	-8.8 dB	-11.4 dB	-15.2 dB
V_π of phase shifter	11.0 V	11.5 V	11.2 V	12.1 V
V_π of amplitude control	22.7 V	21.3 V	20.8 V	19.2 V

Table 3.10: Results of chip measurements made on device in delivered module.

Packaging and Interfacing

In operation the optical input to this device will consist of two optical signals in orthogonal, linear polarization states, whose optical frequencies are frequency and phase locked at the desired microwave frequency. To minimize phase and amplitude variations it is essential that these two orthogonally polarized signals are launched into the birefringence axes (TE and TM) of the waveguide with negligible crosstalk. A polarization maintaining (PM) input fiber is therefore used, with its axes accurately aligned to those of the waveguide. Immediately after the beamforming function it is desirable to resolve the two orthogonal polarized signals into a common axis in order to minimize any environmentally induced phase variations. This is achieved by using an output array of polarizing (PZ) fibers, matched to the four output waveguides, with their polarization axes at 45° to the birefringence axes of the waveguides.

Efficient optical coupling from the PM and PZ single-mode fibers to the smaller waveguide mode of the GaAs device requires some form of imaging. For this experimental device an etched phase lens

approach was used [11]. Whilst this approach may not achieve the highest possible efficiency, it has the advantage of being simple and easy to apply to novel fiber types, such as the PZ fiber, and can readily be used with fiber arrays.

Both the input PM fiber and output PZ fiber array assemblies were based on etched silicon V-groove technology. The output assembly requires the four PZ fibers to be held in an array with their cores in line and separated by 160 µm, preferably with an accuracy of better than ±0.4 µm to produce an excess coupling loss of less than 0.2 dB. The most significant contribution to spacing variations within the array are the concentricity and diameter uniformity of the optical fiber. The PZ fiber used is a new and specialist fiber, and as such its dimensional characteristics are not as well controlled as standard telecoms single-mode fiber. Measurements showed the core to be off-center by as much as 2 µm and the diameter to vary by up to 1.5 µm along its length. Care was taken during the assembly of the array to minimize these variations.

Figure 3.4 illustrates the basic assembly of the four-output PZ fiber array. The input fiber assembly is similar, except it has only a single PM fiber, whose birefringence feature is aligned vertical to within ±5° in order to ensure the polarization crosstalk into the waveguide is better than 20 dB.
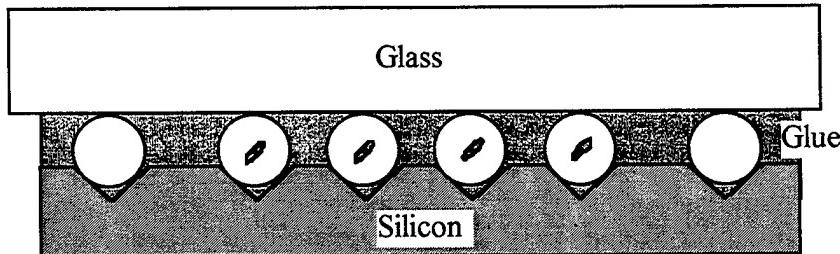

Fig 3.4: Array of four Polarizing fibers aligned at 45° in glass / silicon V-groove assembly

The package design and basic layout of the fibered splitter / beamformer device is illustrated in figure 3.5. In this drawing the package lid is not included in order to illustrate the internal connections. As this is an experimental demonstration device, the assembly used a glue-based packaging technique.

However, all of the assembly processes and designs used are compatible with GMMT's proven ruggedized packaging technology based on solder and laser welding. The assembly of this device into its 'Eurocard' module, and the final testing is summarized in section 3.3.
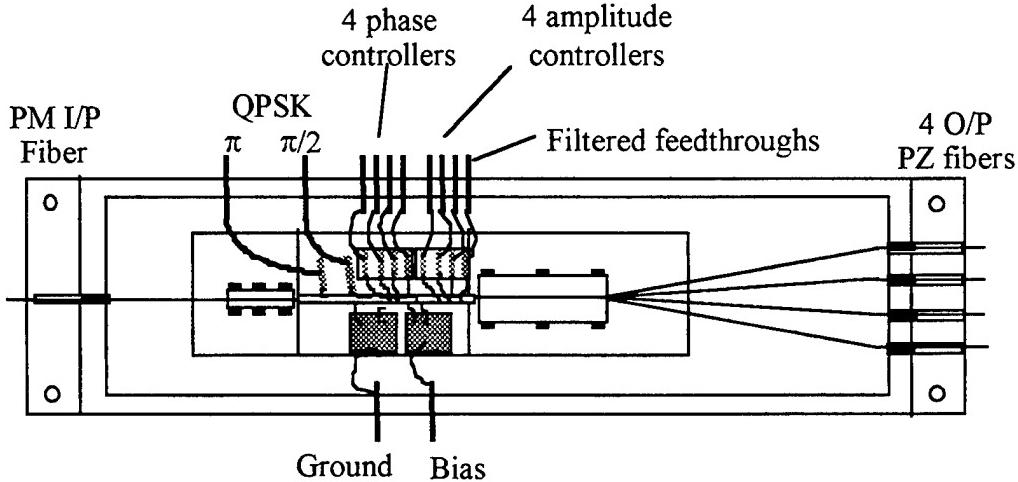

Figure 3.5: Packaged Splitter / Beamformer Device

3.2.2 SSB Modulator

The optical single-sideband modulator is used to modulate an optical carrier with the microwave signal from an antenna element, producing the required optical carrier and single sideband. These signals must also be in orthogonal polarization states for the following optical beamforming function.

Theory / Background

The SSB approach favored by GMMT for microwave optics applications is based on one originally proposed by Désormière et al. [12] and subsequently demonstrated by GMMT [10]. The waveguide design is shown schematically in figure 3.6; it comprises a Y-branch, a coupler structure within which the microwave modulation occurs and an output interferometer.

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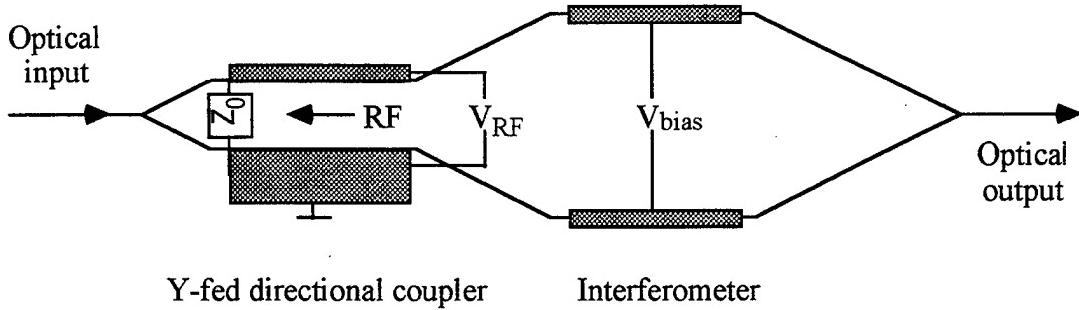
Figure 3.6: SSB modulator waveguide design

The directional coupler is a composite waveguide which supports two normal modes, a symmetric and an antisymmetric mode. The input Y-branch launches only the symmetric mode and the output interferometer acts to transmit or suppress this light, depending on whether the phase bias is set to $0°$ or $180°$. Applying a counter-propagating microwave signal to the directional coupler can induce coupling to the antisymmetric mode. This effect is negligible unless there is phase matching between the microwave signal and the two optical modes along the full length of the directional coupler. Under these conditions a significant fraction of the symmetric light is coupled to the antisymmetric mode with a corresponding upshift in frequency. At the output of the interferometer this frequency shifted optical signal will be a maximum at the $180°$ phase bias condition, thereby producing a carrier suppressed single sideband modulation function.

In a GaAs waveguide the electro-optic effect on TM polarized light is negligible, in which case the waveguide can be designed to transmit TM light unmodulated and with low loss. If linearly polarized light is launched into the device at $45°$ to its birefringence axes the desired device functionality of carrier and sideband in orthogonal polarization states can be realized, as illustrated in figure 3.7.

TE

υ_0

RF Input
(f_0)

TE

$\upsilon_0 + f_0$

Optical
Input

SSB
Modulator

Optical
Output

TM

υ_0

TM

υ_0

Optical Frequency

Optical Frequency
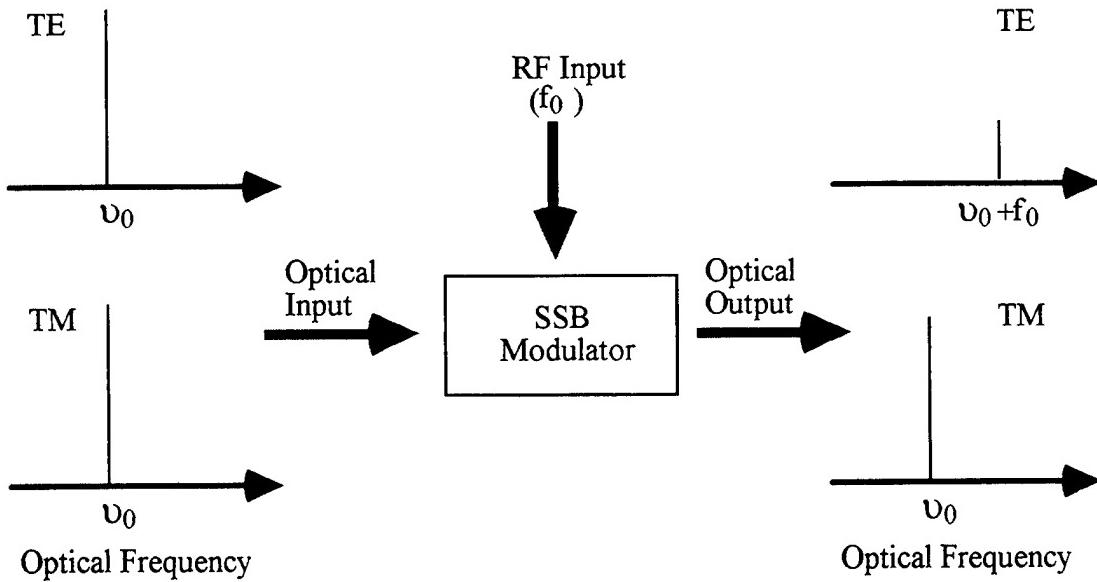
Fig 3.7: Optical input and output spectrum of proposed SSB optical modulator

Device Design

In addition to the SSB modulation and orthogonal polarization characteristic, it is necessary to integrate into this device an optical beamformer. To minimize the complexity it was agreed for this demonstration unit to provide a phase-only optical beamformer.

In implementing the microwave SSB modulator we have exploited many features of previous work on optical intensity modulators carried out at GMMT such as using GaAs waveguide devices, with 50 Ω, 20 GHz traveling wave electrode designs.

Several competing size parameters have to be considered when defining the layout of a waveguide device such as an SSB modulator. In particular it is desirable to have the electrodes as long as possible in order to increase the electro-optic efficiency. On the other hand a short chip is preferred in order to increase the number of devices which can be obtained from a single wafer fabrication. The following design was adopted as a good compromise based on the performance requirements and current best practice.

Modulating electrode length	10 mm	(Predicted V_π = 10 V)
Interferometer electrode length	3.5 mm	(Predicted V_π = 29 V)
Phase shifter electrode length	7.5 mm	(Predicted V_π = 13 V)
Length of chip	23 mm	
No. of chips on 2" wafer	20	
Minimum waveguide bend radius	15 mm	
Approx. waveguide mode radius	2.2 x 1.6 μm	

Table 3.11: Design parameters of the single-sideband modulator and beamformer device

The input and output to the SSB device use 1-to-2 MMI splitters since they are small, have low loss and are easier to control than conventional Y-branches. Figure 3.8 illustrates the design of a single SSB device. This is a composite plot of the various photo-lithographic mask layers, and as such only the larger features, such as the microwave transmission line, electrodes and DC bond pads can be resolved. Three DC controls are used, the SSB bias interferometer, the phase shifter and a fixed +10 V bias, the latter being required to ensure the Schottky contact diodes are reverse biased. In general it is desirable to keep the microwave launch lines as far from the optical facets as is possible, in order to simplify the final package design (figure 3.9). Such a layout was most efficiently achieved by sharing the 7.5 mm long phase shift electrode between the input and output waveguides to the SSB, with each section being 3.25 mm long.
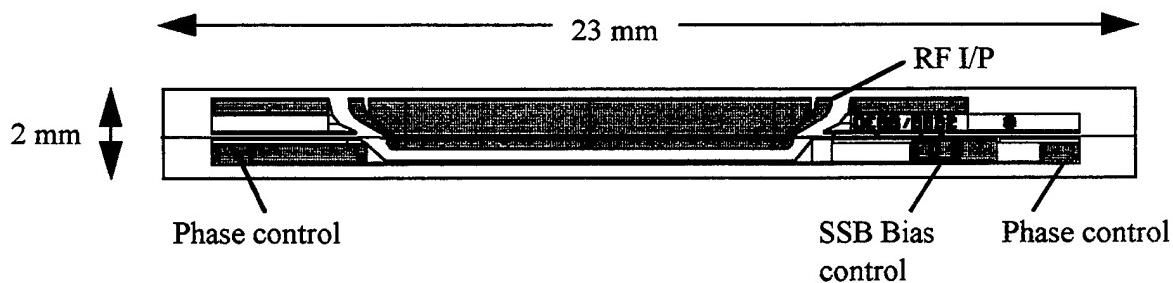

Fig 3.8: SSB Modulator Chip design

Device Characterization

The following table summarizes the results of measurements made on the waveguide chip used in the delivered SSB / beamformer module. These results are typical of devices on the wafer.

SSB Chip	Measured
TE chip loss	4.3 dB
TM chip loss	4.5 dB
Phase shifter V_π	10 V
Optimum bias voltage	25 V
Maximum TE extinction	-16.5 dB
Excess TM loss at optimum bias	0.5 dB
Center frequency	8.9 GHz
Bandwidth	±1.9 GHz

Table 3.12: Results of chip measurements made on device in delivered module.

The microwave results in table 3.12 were measured on a single, sacrificial chip from the wafer (chip #5). The measured frequency performance is shown in figure 3.9.
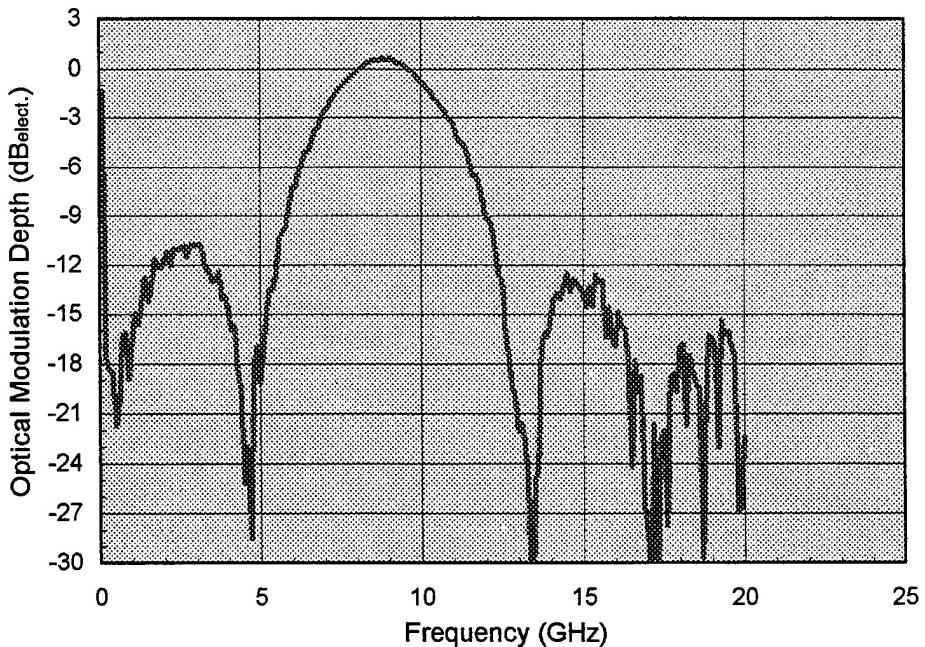
Fig 3.9: Measured frequency performance of chip #5 from the SSB wafer

Packaging and Interfacing

The high power, 1320 nm optical signal launched into the modulator will be linearly polarized, therefore, to ensure equal excitation of the TE and TM polarized states, a polarization maintaining (PM) input fiber is used with its polarization axes set at 45° to the birefringence axes of the waveguide. With the beamformer phase shifter integrated onto the chip it is desirable to provide the output polarization combination function within the module. This is achieved by using a polarizing (PZ) fiber at the output, with its polarizing axis also set at 45° to the birefringence axes of the waveguide.

In order to achieve low loss coupling from the PM and PZ fibers to the GaAs waveguide, the etched fiber lens approach was adopted, as used in the splitter / beamformer assemblies. The fiber assemblies were again based on the use of silicon V-grooves, although in this case only a single fiber was used in both the input and output assemblies. Both the input PM fiber and the output PZ fiber have their birefringence axes aligned at 45°.

The package design and basic layout of the fibered SSB device is illustrated in figure 3.10. In this drawing the package lid is not included in order to illustrate the internal connections. As this is an experimental demonstration device the assembly used a glue based packaging technique. However, all of the assembly processes and designs used are compatible with GMMT's proven ruggedized packaging technology based on solder and laser welding. The assembly of this device into its 'Eurocard' module, and the final testing are summarized in section 3.3.
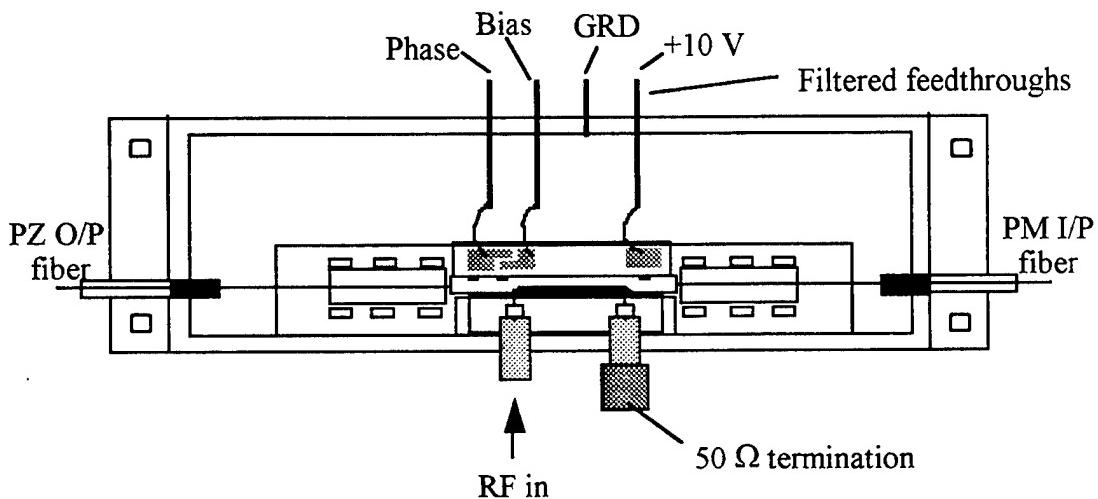

Fig 3.10: Packaged SSB Modulator

3.2.3 Multi-Input Receiver

The multi-input receiver (MIR) is an optoelectronic device for use in the receive link which combines the optical detection and the microwave summation into a single integrated module. This technique was originally developed by GMMT for a phased array antenna contract funded by the European Space Agency [13]. The basic approach is to sum the photocurrents from a linear photodiode array coherently in a single transmission line which forms the feeding structure for a following microwave amplifier.

Theory / Background

The function of the MIR in the optical receive link of a phased array antenna system is to simultaneously detect the optical signals from each of the individual antenna elements, and to add the resulting electrical signals, thus producing an output for a single antenna beam whose direction is determined by the relative phase of the signals producing the coherent addition. This makes possible a circuit configuration in which the microwave signals can be constrained to contribute to a wave which is traveling only in one direction on a microwave transmission line. A 50 Ω termination is required at the far end of the structure, but no signal power is lost to it within the wanted beam. This produces a wide-bandwidth photodetector and combiner whose upper frequency is effectively limited only by the bandwidth of the photodiodes. Figure 3.11 illustrates schematically a four element MIR.
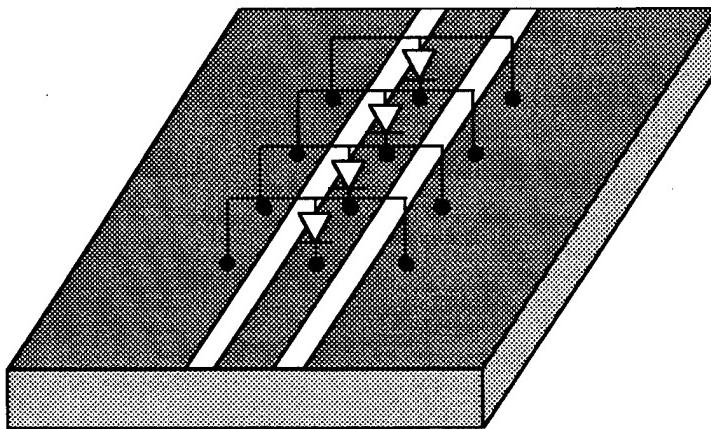

Fig. 3.11: Array of photodiodes feeding a single transmission line

Device Design

As the system demonstrator is based around a four channel, optically controlled, transmit and receive link operating at an optical wavelength of 1320 nm and a microwave frequency of 8 to 9 GHz, the MIR for this demonstrator therefore consisted of an array of four 10 GHz photodiodes. Our preferred technological approach was to fabricate the photodiode array as a single monolithic chip in order to simplify the processing and to control the separation of the devices very precisely. This array was mounted onto a hybrid microwave stripline circuit by the flip-chip solder bonding technique. In this way very close control can be achieved of the position of the array on the stripline as well as the

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parasitic capacitance and inductance associated with their electrical interface. Following our usual practice in microwave detector design, a coplanar waveguide (CPW) transmission line was employed for the feed structure in conjunction with substrate-entry PIN photodiodes. Optical access was through the top of the four element detector array and was achieved by means of an array of four single mode optical fibers.

CPW Stripline

Several competing parameters have to be considered when defining the layout of the microwave coplanar waveguide transmission line. These include having a small photodiode spacing to maximize channel number and ensure a distributed load, as opposed to a large spacing which simplifies both the fiber coupling and the realization of a 50 Ω loaded line. The compromise design is summarized in table 3.13. This uses Alumina as the substrate material for ease of fabrication, resulting in the loaded line having an impedance of less than 50 Ω. A 50 Ω loaded line could be realized with lower capacitance photodiodes, a lower dielectric substrate or wider spacing between the photodiodes in the array. Impedance transformer sections were included at the interface between the loaded section and the 50 Ω termination lines.

Substrate material	Alumina, 630µm
Material dielectric constant	9.8
Effective dielectric constant	5.2
Wavelength in loaded line (@ 8 GHz)	16.2 mm
Separation of photodiodes along line	250 µm
Capacitance per photodiode	0.08 pF
Impedance of unloaded line	82 Ω
Impedance of loaded line	39 Ω
Transformer impedance	44 Ω

Table 3.13: Design parameters of the CPW

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Photodiode Array

The photodiode array consisted of four high speed planar InP/InGaAs photodiodes with solder bonds compatible with the CPW. Table 3.14 summarizes the important device characteristics which were designed to produce photodiodes with a frequency bandwidth of around 12 GHz and a responsivity at 1320 nm of the order of 0.75 A/W.

Device capacitance	0.1 pF/element
Depletion depth	2 µm
Maximum diameter	30 µm
Quantum efficiency	0.7
Separation	250 µm

Table 3.14: Target design parameters of the photodiode array

Device Characterization

The following tables summarize the basic measurements made on the photodiode array itself and after the first stage of assembly of the device used in the delivered unit. The following results are similar for all of the devices and photodiodes within each array.

Photodiode Array	Measured
DC Responsivity (1320 nm)	0.7 A/W
Device capacitance	0.2 pF

Table 3.15: Results of measurements made on photodiode array

MIR fixed in Package Base	Measured
DC Responsivity (1320 nm)	0.7 A/W
RF Responsivity @ 8 GHz (1320 nm)	0.4 A/W
Output VSWR	2.1:1

Table 3.16: Results of measurements made on the MIR assembled in its package base

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Packaging and Interfacing

Fiber interfacing to the photodetector array involved mounting four single mode (SM) fibers into V-grooves etched into silicon designed to match the 250 μm spacing of the photodiodes. The V-groove fiber assembly was polished to obtain an optically flat face so that it could be brought into close proximity to the detector array for good coupling efficiency.

The package design and basic layout of the fully fibered four channel MIR is illustrated in figure 3.12. In this figure one side wall is not included in order to illustrate the internal assembly. The figure also shows the interface to the bias tee and post amplifier as used in testing and in the final module assembly. The assembly of this device into its 'Eurocard' module and the results of final testing are summarized in section 3.3.
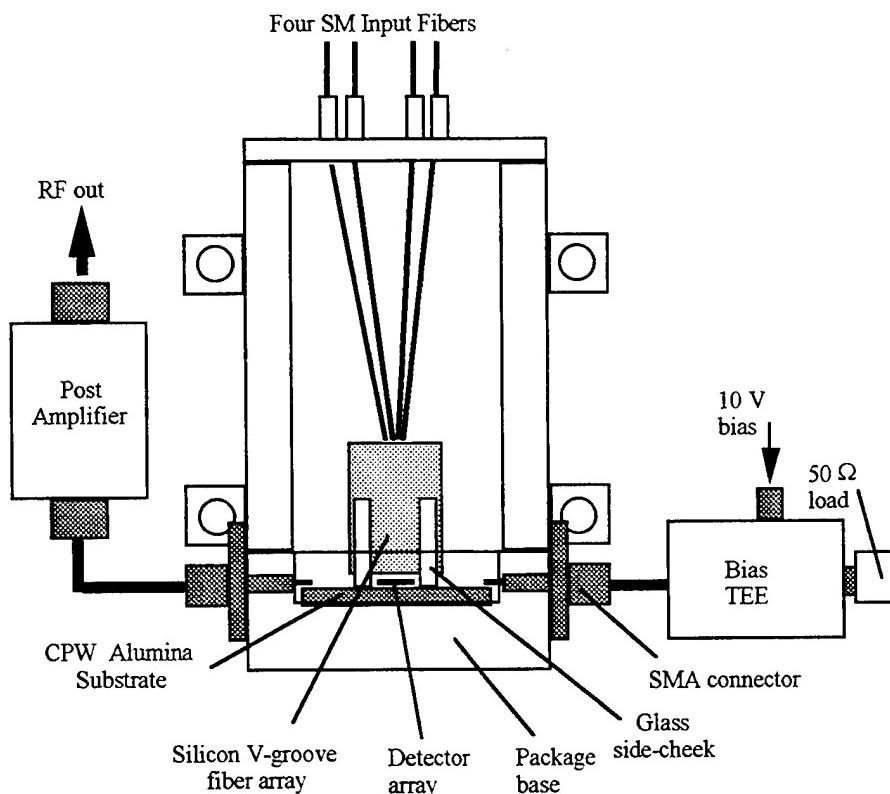

Fig. 3.12: Schematic of a packaged MIR illustrating the basic assembly interfaces.

3.3   Integration and Characterization of Experimental System

The integration of the previously described optical devices into the experimental system consisted of mounting them into 'Eurocard' holders with suitable optical, electrical and microwave front panel terminations and connectors as illustrated in figure 3.2 and shown in the photograph of figure 3.13. Electrical signals are provided by circuits mounted within the module, powered via the back rail of the 19" rack. Details of this assembly stage and the internal layout of the cards are included in the Design and Build report [5]. The following sections describe the final testing of each module and discuss the implications of the results obtained.
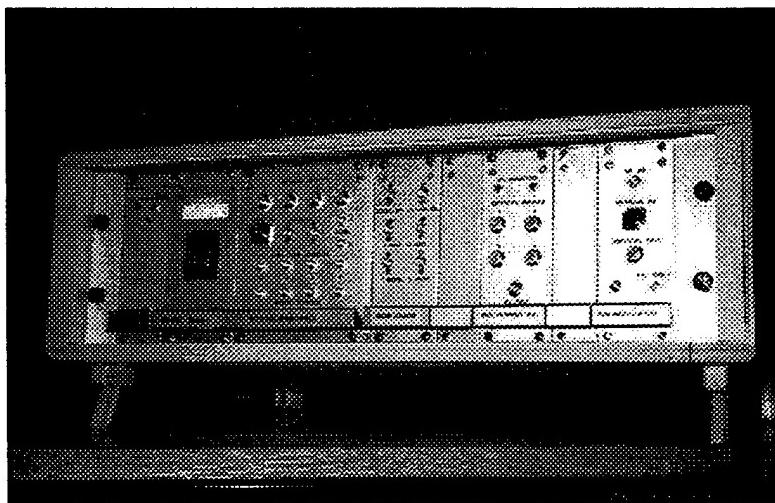
Fig. 3.13: Photograph of rack mounted experimental system.

3.3.1   Splitter / Beamformer Module

The module assembly consists of the packaged, electro-optic, integrated splitter / beamformer device plus two QPSK interface circuits. These circuits were pre-set during assembly to provide the correct voltage levels to drive the π and $\pi/2$ optical phase modulators. A photograph of the completed card assembly is shown in figure 3.14.

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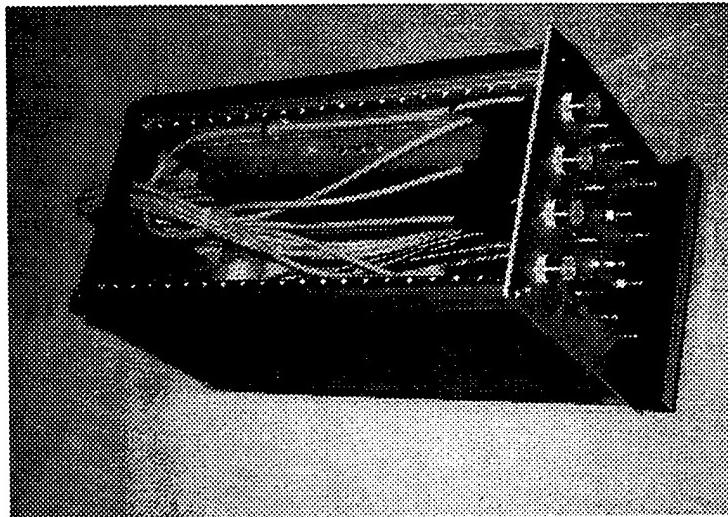
Fig. 3.14: Photograph of splitter / beamformer card assembly.

Module Characterization

Characterization of the complete splitter / beamformer module was performed by launching 1320 nm light into the input PM fiber, with the desired polarization state, and monitoring the optical output of each channel with a suitable photodiode. This basic set-up is illustrated in figure 3.15.

The optical losses were measured by comparing the input and output signals, with the optical attenuation set for maximum transmission. The optical attenuators were assessed by applying a voltage to the relevant input port and monitoring the intensity change on the optical output. The phase modulators were assessed in a similar way but with the polarization of the optical launch set at 45° to the axes of the input PM fiber. In this case a complete change in the output intensity from maximum to minimum corresponds to a relative phase shift of π between the two polarization states. The polarization crosstalk level was determined indirectly by launching either TE or TM into the input PM fiber, modulating the phase modulator by more than π, and noting the residual intensity modulation.

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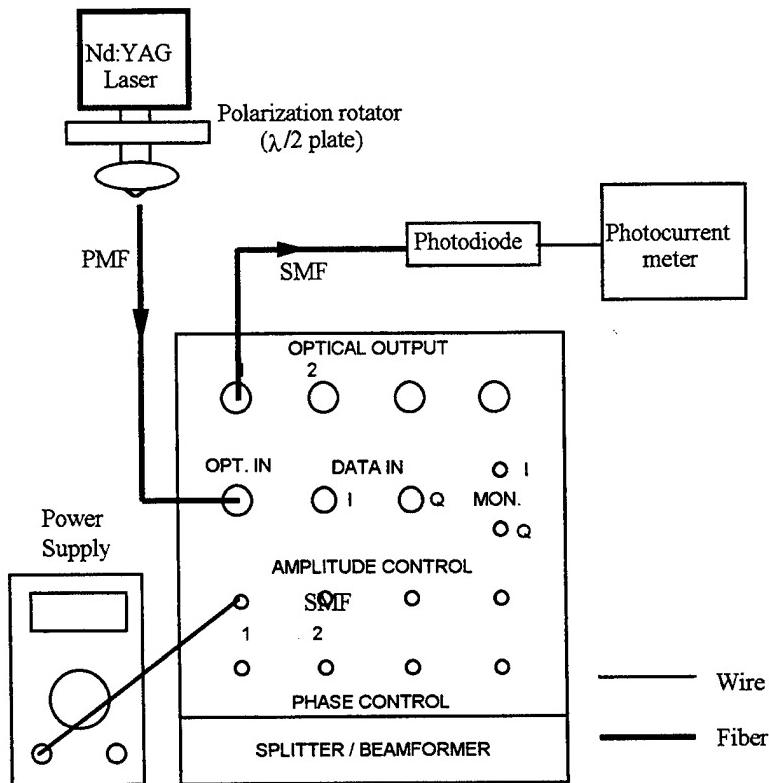
Fig. 3.15: Set-up used to measure the performance of the splitter / beamformer module.

The only RF assessment needed was of the QPSK modulators, where it was necessary to determine their maximum frequency response. Figure 3.16 illustrates the basic set-up used. A binary word produced by the generator was applied to the QPSK coder module, along with a suitable clock signal. The ECL outputs from this module were applied directly to the QPSK inputs of the splitter / beamformer module, as well as being monitored on the oscilloscope. With the optical signal launched at 45° to the axes of the input PM fiber, a QPSK phase modulation produced an optical intensity modulation at the device output, which was detected with a suitable photodiode and monitored on the oscilloscope. Driving the 'Q' input only the output optical word should match the input and be 100% modulated (π phase modulation). The same will result for the 'I' input except that the output intensity modulation depth will be approximately 50% ($\pi/2$ phase modulation). The maximum input data rate was taken as when the intensity modulations dropped by 3 dB, and was measured to be 80 MBit/s.
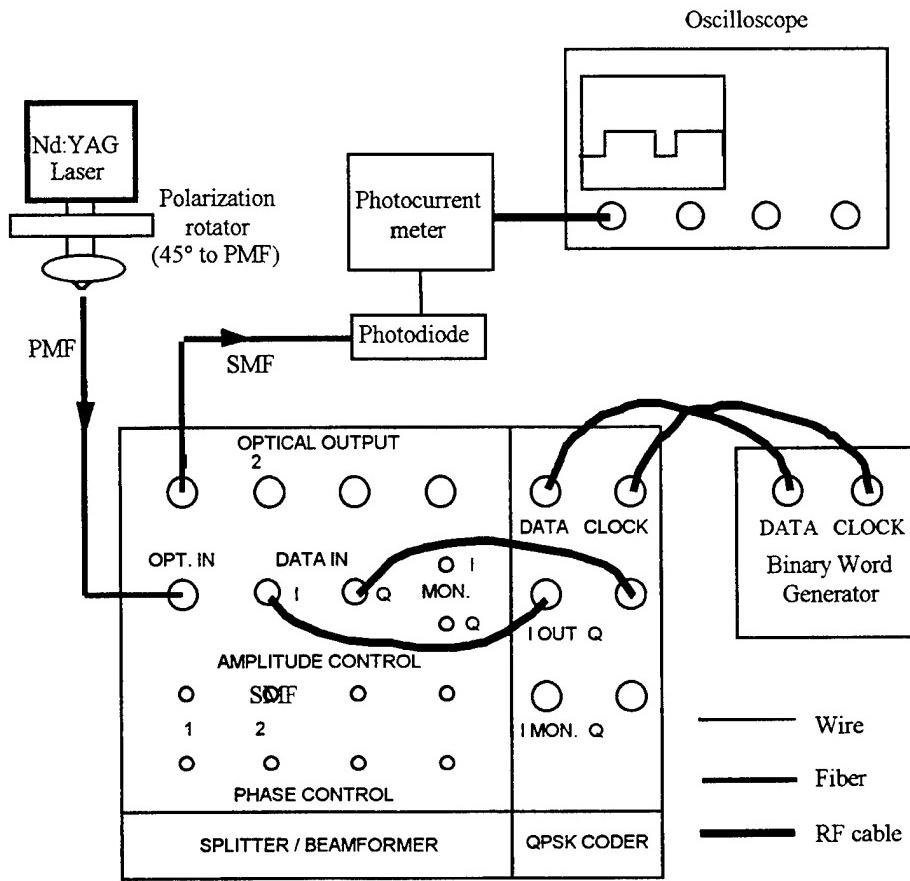
Fig. 3.16: Set-up used to measure the QPSK modulation of splitter / beamformer module.

Measured Module Performance

Table 3.17 compares the target and measured performance values for the delivered splitter / beamformer module. The module achieved the full functionality and compared to the original target performance produced a higher data rate QPSK optical modulator and lower drive voltage phase and amplitude controls. Areas where the completed module did not quite meet the target values are the optical loss, polarization crosstalk and maximum attenuation. The following paragraphs briefly discuss the reasons for these discrepancies and what can be done to overcome them in future builds.

| | | Measured | | | |
PARAMETER	Target	1	2	3	4
Wavelength	1320 nm	1320 nm	-	-	-
Max. QPSK data rate	40 Mbit/s	80 Mbit/s	-	-	-
I/P PM connector loss[1]	0.5 dB	1.0 dB	-	-	-
Fiber-Fiber device loss: TE	21 dB	26.6 dB	27.1 dB	25.0 dB	23.3 dB
(at min. attenuation) TM	21 dB	26.0 dB	26.5 dB	26.3 dB	25.2 dB
O/P SM connector Loss[1]	0.5 dB	0.7 dB	0.8 dB	0.5 dB	1.5 dB
Polarization crosstalk	-20 dB	-13.2 dB	-13.3 dB	-16.3 dB	-17.7 dB
V for π phase shift	15 V	11.1 V	11.4 V	10.6 V	11.9 V
V for min. amp. atten.	0 V	0 V	0 V	0 V	0 V
V for max. amp. atten.	±30 V	22.4 V	20.4 V	21.3 V	18.0 V
Maximum attenuation (of TE)	10 dB	9.6 dB	9.7 dB	9.3 dB	18.9 dB

[1] These connector losses are measured with respect to a reference connector, the effect of core concentricity errors with the actual connector used could result in slightly different values.

Table 3.17: Comparison of measured and target performances of splitter / beamformer module

Optical Loss

The optical loss is higher than the target by up to 6 dB in the worst case, and the loss variation across the array is ±2 dB for the TE polarized light. Up to 4 dB of this excess loss is a result of variations in the concentricity and diameter of the PZ fiber within the output V-groove array and movements on fixing it in place. The rest is made up of an additional 1 dB excess chip loss and 1 dB excess lensed fiber coupling loss as compared to the original design.

From previous experience we are confident that the desired chip loss and fiber-to-waveguide coupling loss can be achieved. The combination of a fiber concentricity error and small mode GaAs waveguide will always result in significant loss variations across a fiber waveguide array. GMMT are actively investigating mode-tapering techniques within the GaAs waveguide itself in order to increase the

interface waveguide mode and hence improve its tolerance to fiber position and concentricity. Such an approach, in parallel with tighter diameter and concentricity control of the PZ fiber is essential for the implementation of low cost passive alignment techniques.

Polarization Crosstalk

The indirect method used to measure the polarization crosstalk on the packaged device resulted in values higher than expected from the chip measurements. Subsequent measurements on bare chips from the same wafer indicated that this was a measurement artifact caused by voltages applied to the input phase shifter influencing the 1-to-4 MMI coupler, producing small output intensity changes. The true polarization crosstalk value is believed to be better than -20 dB, as measured on the chips and so is not considered to be a problem.

The effect is believed to be due to residual slab light getting into the MMI and influencing its performance. Further investigation is required to confirm this in order that device designs can be implemented to minimize any such effects.

Attenuation Control

The maximum optical attenuation achieved was slightly under the target specification for three of the four channels. This appears to be a combination of the initial design precision of the 1-to-2 MMI couplers used at the input and output of the Mach Zehnder attenuators, as well as the effect of small changes in their splitting ratio with applied electric field due to the presence of residual slab light.

3.3.2 SSB Module

This module contains the packaged SSB modulator device plus a dual voltage bias control circuit. One voltage line supplies the fixed 10 V bias required by the semiconductor modulator to fully deplete its p-n junction. The other voltage line is adjusted on assembly to set the output bias interferometer of the SSB modulator for optimum TE carrier suppression. A photograph of the completed card assembly is shown in figure 3.17.

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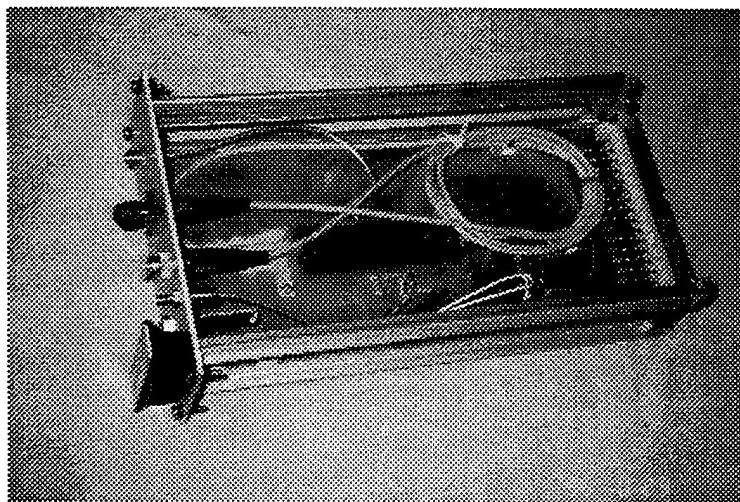
Fig. 3.17: Photograph of SSB modulator card assembly.

Module Characterization

Figures 3.18 and 3.19 illustrate the set-ups used to characterize the complete SSB module prior to shipment to CECOM. The set-up illustrated in figure 3.18 uses an HP 8703 lightwave analyzer to measure the modulation frequency response of the SSB modulator. The optical signal was from a 1320 nm, diode pumped Nd:YAG laser, providing about 1 mW of optical power into the PM fiber input. In order to improve the detected signal-to-noise ratio, a high power drive amplifier was used, providing approximately +23 dBm of microwave power to the SSB modulator. Figure 3.19 shows an example frequency response measured on the module. For this measurement no voltage was applied to the phase shifter.

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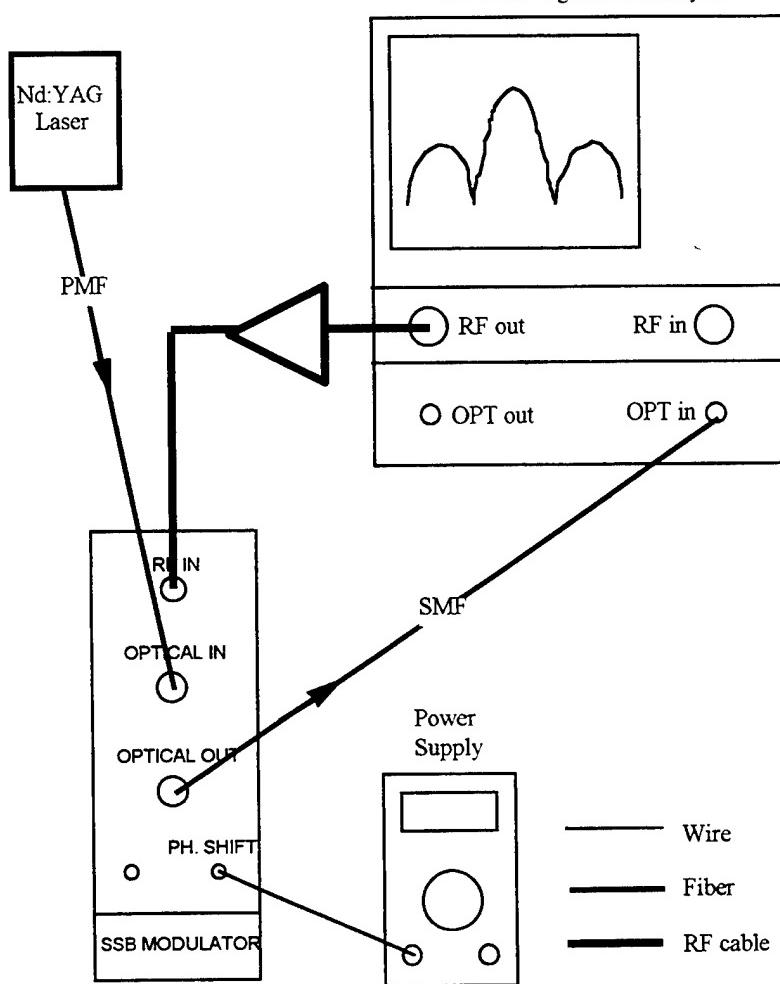
Fig 3.18: Set-up used to measure frequency response of SSB module

CH1 E/O   log MAG   5 dB/ REF -60 dB

START   .130 000 000 GHz   STOP 20.000 000 000 GHz
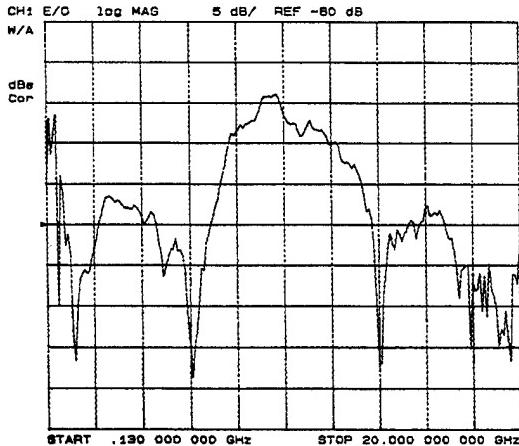
Fig. 3.19: Measured frequency performance of delivered SSB Module

Figure 3.20 illustrates the set-up used to assess the level of upper sideband and image sidebands directly. The same narrow linewidth 1320 nm source is used, but in this case the microwave drive is a single frequency from a synthesizer. The optical output is monitored in a scanning Fabry-Perot interferometer in order to directly see the optical spectrum. To resolve the 9 GHz sidebands from the carrier it is necessary to use a narrow linewidth optical source such as a diode pumped Nd:YAG laser, which has a single-frequency output with a linewidth the order of 1 kHz. This measurement enables the modulation efficiency and image sideband rejection to be measured.

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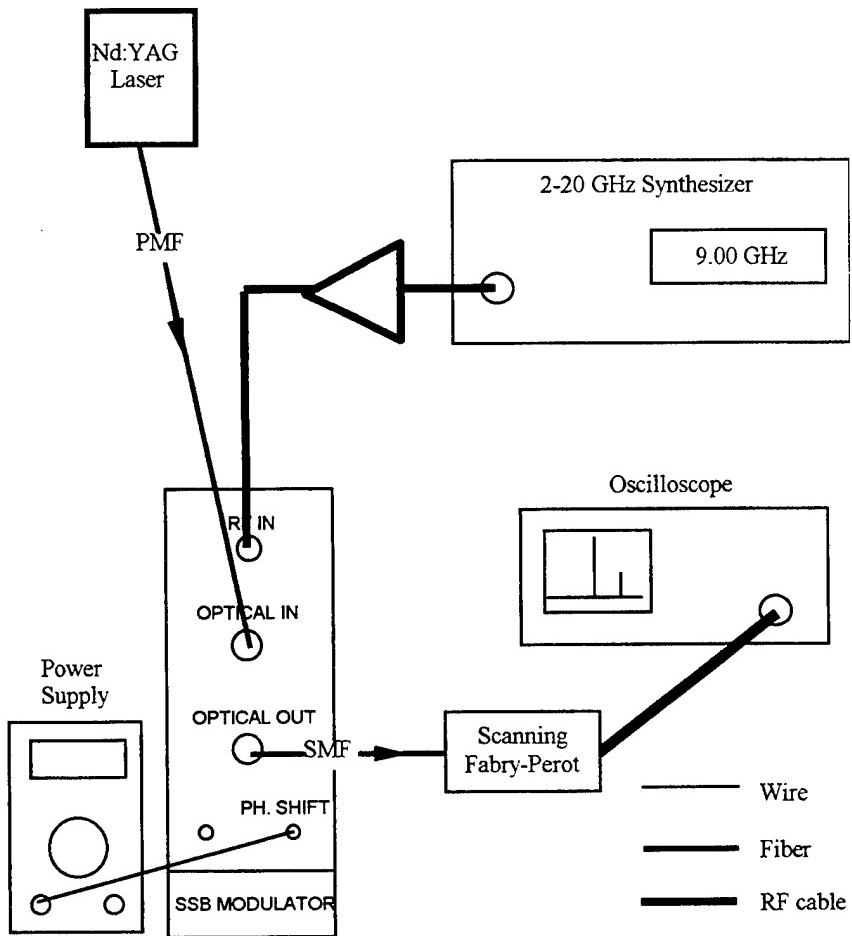
Fig 3.20: Set-up used to measure optical spectrum transmitted by the SSB modulator

Measured Module Performance

Table 3.18 compares the target and measured performance values for the delivered SSB module. This module achieved the full functionality, realizing the target center frequency and exceeded the target bandwidth and conversion efficiency. Areas where the completed module did not quite achieve the target values are the optical loss, the carrier suppression and the operation of the phase shifter.

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PARAMETER	Target	Measured
Wavelength	1320 nm	1320 nm
I/P PM connector loss[1]	0.5 dB	0.8 dB
Fiber-Fiber device loss (at optimum bias)	15 dB	20 dB
O/P SM connector loss[1]	0.5 dB	0.5 dB
Drive power for 10% SB conversion	+30 dBm	+23 dBm
Maximum conversion frequency	9 GHz	8.9 GHz
3 dB conversion bandwidth	2 GHz	4 GHz
Carrier suppression	-20 dB	-10 dB
V for 2π phase shift	30 V	~20 V[2]

[1] These connector losses are measured with respect to a reference connector, the effect of core concentricity errors with the actual connector used could result in slightly different values.
[2] Implied from chip measurements, could not measure directly.

Table 3.18: Comparison of measured and target performances of SSB module

Optical Loss

The high optical loss is a combination of excess chip loss and higher-than-predicted fiber coupling losses. A low optical loss is essential in this application, in order to achieve a high dynamic range optical link using a reasonable power optical source. Lower device losses should be possible in future builds, in view of the performance routinely achieved in standard GMMT GaAs waveguide modules. Other techniques, such as tapered waveguides matched to the optical fiber, are being developed at GMMT which will reduce fiber interface losses and also ease the assembly tolerances.

Carrier Suppression

The indirect method used to measure the carrier suppression on the module produced a value of only -10 dB. Subsequent investigations on other SSB chips from the same wafer showed a similar increase in the TE transmission as a result of applying a voltage to the phase modulator. The effect appeared to be caused by non-guided light coupling into a 1-to-2 MMI splitter producing a variable level of unwanted antisymmetric mode in the directional coupler modulator section. This effect can be

minimized by improving the spatial filtering of the unguided light and not having the phase shifter electrodes on the input waveguide. In the delivered module, the actual carrier suppression is believed to be around the -16 dB level, as measured on the chip prior to packaging. This suppression level is still somewhat higher than the desired target of -20 dB, possibly due to a small intrinsic asymmetry in the 1-to-2 MMI splitters.

Phase Shifter

The V_π of the phase shifter was measured on the chip to be around 10 V, but it was not possible to measure it when in the fibered device. This was due to the previously discussed observation that applying a voltage to the phase shifter detuned the SSB modulator by increasing the level of antisymmetric light launched into the directional coupler section. It was possible to apply only about ±2 Volts (~±30° phase shift) before significant levels of TE carrier were generated.

3.3.3   MIR Module

This module contains the packaged four channel MIR, an output 2 - 12 GHz amplifier and a bias tee. In addition simple electrical circuits provide the power supply to the amplifier as well as the +10 V reverse bias to the photodiodes. This bias line also contains a 1 kΩ resistor, the photocurrent being monitored on the front panel of the module as a voltage across this resistor. A photograph of the completed card assembly is shown in figure 3.21.
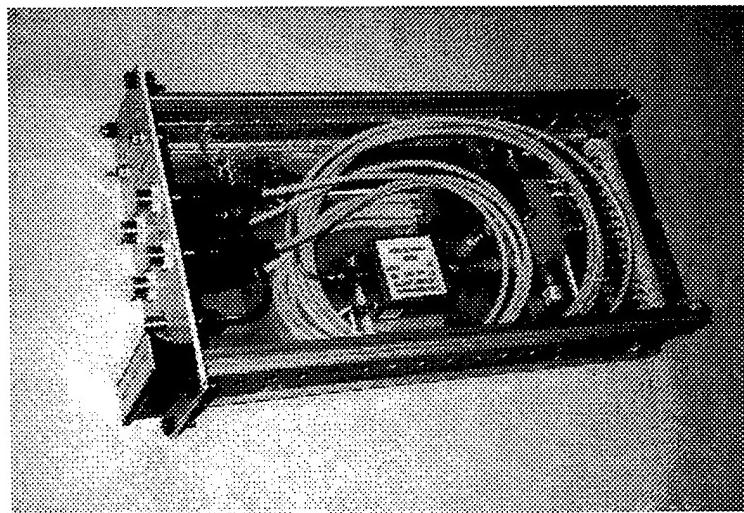
Fig. 3.21: Photograph of MIR card assembly.

Module Characterization

Figure 3.22 illustrates the set-up used to characterize the complete MIR module prior to shipment to CECOM. The HP 8703 lightwave analyzer (1300 nm) was used to measure the frequency response of each of the four optical ports to the MIR and also to measure the VSWR of the complete unit. It was also possible to measure the DC responsivity by coupling a known optical power into each fiber and monitoring the resulting voltage across the 1 kΩ bias resistor. This measurement was used to confirm that the optical loss of the connectors was less than 0.5 dB.
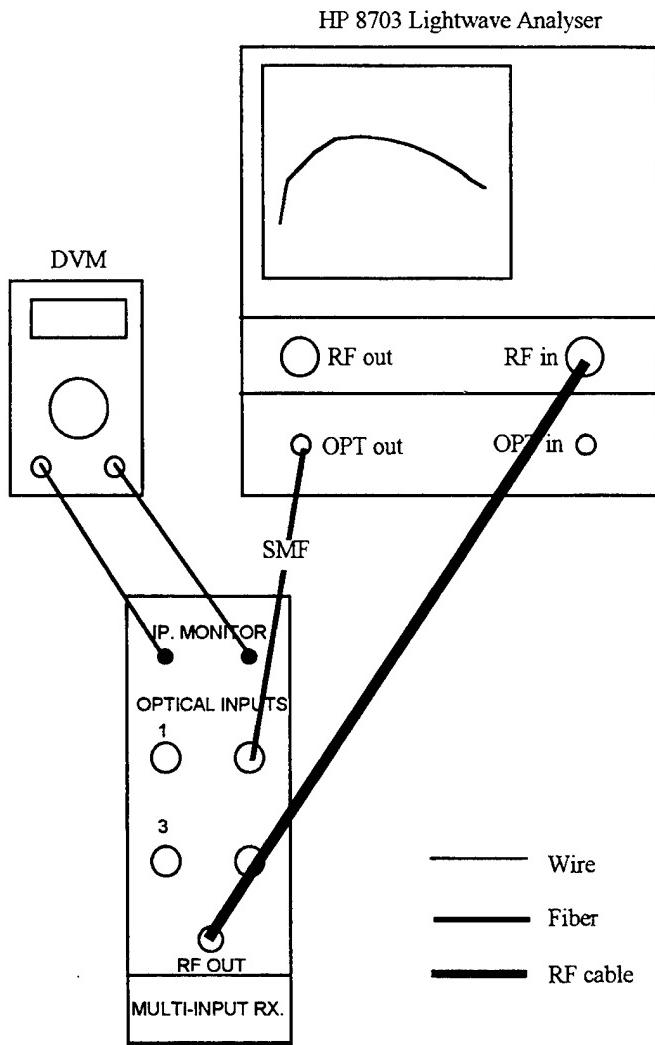
Figure 3.22: Experimental set-up used to assess MIR module

The frequency response of a typical channel is illustrated in figure 3.23. This measured performance combines the effect of the MIR frequency response, the loss of the optical connector and the gain of the post amplifier. The lower frequency is therefore determined by the post-amplifier to be 2.5 GHz, whereas the upper frequency is limited to 7 GHz by the frequency response of the MIR photodiode.
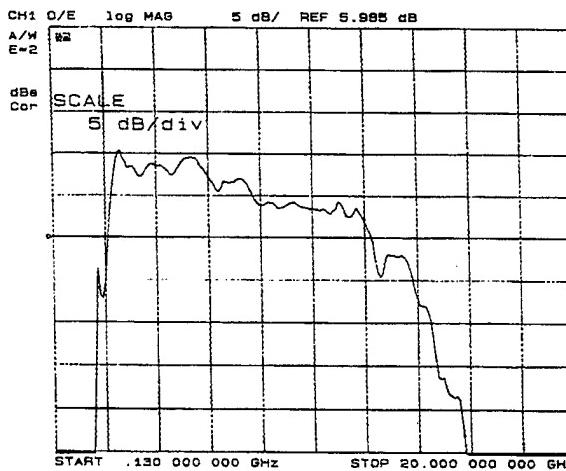
Figure 3.23: Frequency response of a typical channel of the delivered MIR module

Measured Module Performance

Table 3.19 compares the target with the measured performance values for the delivered MIR module and illustrates that the full functionality was achieved. In the final module configuration it is only possible to assess the overall frequency response, the DC responsivity and the VSWR. The internal photodiode performances are assumed to be as measured on the MIR device prior to module assembly.

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		Measured			
PARAMETER	Target	1	2	3	4
Wavelength	1320 nm	1300 nm	-	-	-
Amplifier Gain at 8 GHz	15 dB	19 dB	-	-	-
Amplifier NF at 8 GHz	3 dB	2.5 dB	-	-	-
O/P VSWR (6 - 12 GHz)	2.0 : 1	1.8 : 1			
I/P PM connector loss[1]	0.5 dB	-	-	-	-
DC Responsivity of photodiode	0.70 A/W	0.71 A/W	0.68 A/W	0.70 A/W	0.71 A/W
8 GHz Responsivity of photodiode	0.6 A/W	0.4 A/W	0.4 A/W	0.4 A/W	0.4 A/W
Lower 3 dB bandwidth	6 GHz	2.5 GHz	2.5 GHz	2.5 GHz	2.5 GHz
Upper 3 dB bandwidth	12 GHz	7 GHz	7 GHz	7 GHz	7 GHz

[1] Not measured directly, results before and after connector attach suggest they are all less than 0.5 dB.

Table 3.19: Comparison of measured and target performances of MIR module

Frequency Response

The main discrepancy between the target and measured module performance is the reduced upper frequency bandwidth and the reduced responsivity at 8 GHz. These in turn are a direct consequence of the higher than expected photodiode capacitance, which produces an impedance mismatch in the loaded CPW structure resulting in ripples in the frequency response at around 8 GHz. Further investigation is required to minimize the photodiode capacitance within an array and also to identify the cause of any variations in order that accurate 50 Ω loaded lines can be achieved.

3.4 Conclusions and Discussion

In summary, we have successfully designed, fabricated and assembled the critical optoelectronic components required to demonstrate transmit and receive mode coherent optical beamforming. Due to the advanced nature of the components and the optical technology involved, this equipment was supplied as an experimental demonstrator with a limited number of channels (four element beamforming control). The equipment was, however, designed, built and assembled in a modular

form which enables different aspects of an optical beamforming link to be investigated as well as being compatible with future expansion using additional or more advanced modules.

The demonstration contained three custom built optoelectronic modules. The splitter / beamformer module contained a 1-to-4 way optical splitter monolithically integrated with individual phase and amplitude control on each channel as well as a common input QPSK modulator. The SSB module contained a monolithic chip which integrated the optical modulation, polarization handling and optical beamforming into a single device. The MIR module contained a 4-element, X-band photodiode array integrated with a microwave combiner.

Each of the delivered modules achieved the target functionality and performance requirements in all but a few parameters. The following table summarizes the experimental transmit and receive link performances predicted to be achievable with the delivered modules in combination with the assumed CECOM components (see section 3.1).

PREDICTED LINK PERFORMANCE		Target Modules	Actual Modules
Transmit Link	O/P noise power	-159 dBm/Hz	-164 dBm/Hz
	O/P RF power	-25.4 dBm	-42.8 dBm
	O/P CNR	133 dB Hz	121 dB Hz
Receive Link	Small signal link gain	-35.5 dB	-39.1 dB
	Noise figure	59 dB	63 dB
	O/P RF power (0 dBm drive)	-35.5 dBm	-39.1 dBm
	O/P CNR	115 dB Hz	111 dB Hz
	SFDR (1 Hz bandwidth)	109 dB	107 dB

Table 3.20: Predicted performance of demonstrator links

The following paragraphs briefly summarize the design improvements required in order to develop the existing demonstration equipment into a fully operational, optically controlled, phased array RAP system.

Splitter / Beamformer

The RAP system requires at least 256 channels, which can most sensibly be achieved by combining several sixteen-channel optical beamformer devices. A sixteen-channel device will require a more careful design of the MMI splitter, but the additional channels are expected to have only a small impact on the overall length of the chip; in fact the chip could be shorter since it will not require the input QPSK modulator sections. If desired this additional chip length could be used to reduce the beamformer control voltages.

A practical optical beamforming system will be a hybrid assembly containing several 1-to-16 splitter / beamformer devices, preceded by an active splitter which contains integrated optical amplification. It is desirable to maintain a low optical loss and polarization crosstalk throughout the system, as well as keeping the number of optical interfaces and the optical path lengths small. The design of the assembly, interfacing and packaging approach for a full optical beamformer unit is therefore just as important as achieving the required performance and functionality within the individual optical components.

SSB Modulator

Two of the most critical SSB device parameters are its optical loss and its modulation efficiency, since these directly affect the link dynamic range. Lower loss modules are expected in future builds, but the modulation efficiency achieved in this demonstrator was about 13 dB below the ultimate design requirement, necessitating significant development. It is possible to improve the efficiency by reducing the waveguide mode size and thereby increasing the electro-optic overlap. However the need to maintain a low TM loss limits the achievable improvement to about 10%. Increasing the length of the SSB modulating section is possible, but this will reduce the bandwidth. Current RAP requirements could tolerate a doubling of the electrode length yielding a 6 dB increase in modulation efficiency. More radical designs should also be considered, such as parallel electro-absorption modulators [14], which have much lower drive voltages but are less tolerant to wavelength, fabrication and bias settings.

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As the integrated SSB modulator and beamformer must fit into an X-band T/R module, it would be preferable for both the input and output waveguides to be on the same facet, rather than opposite ones as in the conventional approach (figure 3.8). Folded SSB modulator designs can be envisaged to achieve this functionality, which will produce shorter, but wider devices.

MIR

A single MIR for the RAP communication antenna would require a 256 element photodiode array; such an array is at the upper end of present technology and a more practical approach would be to use several smaller units (e.g., 16 diodes) in parallel. A 250 µm photodiode separation, as used in this demonstration system would require active CPW regions to be 3.8 mm long for 16 diodes or 63.8 mm long, for 256 diodes, and the longer lengths may have loss and dispersion implications. A 125 µm separation is possible with standard fiber, and by etching the fiber or using smaller diameter fibers, spacing down 80 µm or less has been used. The latter example would allow up to 50 photodiodes to be fitted into a length of less than 2 mm. Such close spaced photodiodes will increase the loading and hence reduce the effective impedance of the CPW. This would make it difficult to achieve a 50 Ω loaded line; however, for narrow band communication applications an impedance transformer could be used. Due to practical constraints such as yield of photodiodes and solder bonds it may well be more effective to use a hybrid approach based on several small (~16 element) parallel arrays (e.g., 16 x 16) and to electrically combine their outputs using Wilkinson combiners integrated onto a common substrate containing the coplanar waveguides. Such coherent in-phase combiners can have very low losses (<1 dB).

The vertical attachment of the fiber array to the photodiode array was adopted as the simplest variation of a standard GMMT technique for this demonstration build. In a practical assembly an alternative, less labor-intensive approach would be needed. Fibers in V-grooves will probably still be used as they are the most convenient way of providing precise separation of an array of fibers. However, some form of passive or semi-passive alignment technique would be required, such as etched or solder bond alignment features or precision machined mechanical locations.

4. RECOMMENDATIONS

This program has analyzed in detail the application of optical technology to phased array antennas for communications on the move and demonstrated most of the critical optoelectronic components. A significant result of the study is that a modest level of optical and microwave integration can provide an advantage in all the systems investigated. One of the main advantages is a reduction in the amount of hardware within the T/R modules through remoting the beamforming and distribution functions to the central unit. In some applications an overall mass and power saving is also provided by the use of optical beamforming techniques. Furthermore the optical beamforming approach enables some common optical modules to be used, in particular the optical feed network and beamformer for the transmit link.

As a result of the study and build phase it is now possible to identify those technology areas which require further research or development in order to realize a full, practical, optically controlled phased array RAP antenna in the near future. These are briefly summarized below.

OPLL Transmitter

The RAP system requires a coherent, two-frequency, orthogonally polarized optical transmitter operating at SHF. The most efficient, robust, compact and flexible design would be one based on optical phase locking of two DFB lasers. Such an OPLL transmitter requires the development of frequency tunable laser diodes with appropriate modulation characteristics, an optical combining circuit and feedback electronics, all with very low loop delay. A prototype device based on hybrid assembly techniques is being developed in a parallel program funded by CECOM [9].

The use of an integrated optical approach combining the lasers and optical circuit in one OEIC device will simplify the assembly and minimize the number of optical interfaces. Development is required in

OEIC technology in order to achieve all of the optical functions with the desired performance on a single, monolithic device.

A greater OPLL performance advantage can be obtained by integrating the feedback electronics (photo-receiver, amplifier, mixer and filter) into a single MMIC. This significantly reduces the loop delay and hence improves the phase noise reduction of the loop. MMIC technology is capable of integrating all of these functions, however a single device must be carefully designed in order to be compatible with slave lasers having differing FM responses.

Active Splitter

To assemble a full 256 channel optical beamformer requires not only the development of suitable optical splitter / beamformer devices, but also an active splitter which combines splitting and optical amplification functions. This unit has been adopted as a basic building block for the transmit link feed network of all systems analyzed in this study. It could also be used in other phased array applications as well as signal distribution in telecomms or other analogue systems.

In the near term, hybrid devices based on polarization maintaining EDFAs and passive optical splitters can be used, though with some restrictions. The ideal active splitter is a monolithic device containing a polarization maintaining splitter and optical amplification. Such a design will be small, modular, and introduce minimal birefringence variations with temperature. An InP based OEIC is currently perceived as the best alternative. Device structures similar to those required have been demonstrated in the laboratory for telecomms applications. Such work is of benefit to this application, but further development will be needed due to the different requirements of the phased array system, such as high saturation powers, high linearity, low polarization crosstalk and low differential phase effects. A possible future alternative, which must also be considered, is a device based on doped waveguide amplifiers.

Splitter Beamformer

Suitable integrated optical splitter / beamformer devices can be designed and fabricated using existing technology, as delivered in the demonstration equipment. The main device development work is to optimize the performance and yield. Developing suitable packaging and interfacing approaches is arguably more important, and is considered below. However, the design of devices such as the active splitter and splitter / beamformer must be performed in parallel with the development of their packaging and interfacing techniques.

Devices based on GaAs waveguide technology are considered to be the most suitable due mainly to their small size and high tolerance to environmental changes. The devices fabricated in the demonstration phase of this project represent the state-of-the-art. Therefore, the areas which require addressing are the optical interface losses, uniformity and stability of the MMI splitters and the maximum achievable optical attenuation.

Fiber Cable and Interconnection

An optical remoting design has been adopted for the transmit link of all three systems because it simplifies the components within the antenna unit. This approach requires the interconnection of a large number of optical fibers from the central unit to each antenna panel. The three examples considered in this study require at least 256 fibers for the transmit link and anything from 32 to 256 for the receive link of each antenna panel. The interconnection of such large arrays of single mode optical fiber requires the development of efficient multi-way optical connectors. Sixteen way fiber ribbon connectors are now becoming available and some stacked connectors containing over 100 fibers have been reported. Such connectors are not immediately useable in these applications since further development will be needed to ruggedize them for use in a military environment. This is one critical technology which could be developed for other applications such as optical backplanes.

T/R Module Design

The limited space available within the T/R module of an active phased array antenna makes it difficult to package the necessary optoelectronic and microwave functions within it. This gets harder for

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millimeter wave systems where the T/R modules are even smaller. One of the major advantages of an optical beamforming approach is that it can simplify and reduce the size and number of components required in each T/R module.

Many of the optoelectronic components and functions required for the T/R designs described in this report already exist. However, most are not in a form compatible with packaging into the required T/R module shape and integrating with other optical and microwave components. This particular packaging problem is very specific to phased array antenna applications and requires considerable investigation and development if practical optically controlled T/R modules are to be realized.

Within the Tx module, the required photo-receiver and amplifier chain can be fabricated and assembled with conventional technology, and made to fit within a 10 mm wide unit. A much smaller assembly would be useful for higher frequency applications or if a duplex T/R module is to be used. This could be realized with the development of a common optical / microwave assembly approach whereby the photodetector, pre-amplifier and amplifier chain are all attached to a common base. With our in-house capabilities in both advanced optoelectronic and microwave packaging, GMMT is in a good position to develop such an assembly approach.

Within the Rx module a similar common assembly would be an advantage, but in this case the optoelectronic device is an optical modulator (DSB or SSB). Fitting conventional modulator devices into the space available within a T/R module requires the development of a folded path design, whereby the optical inputs and outputs are on one edge and the microwave input on the other.

SSB Modulator

One of the most critical optoelectronic components in the receive link of an optically controlled phased array antenna is the single sideband optical modulator. GMMT have demonstrated devices with the required functionality, but further research and development work is required to achieve the desired modulation performance, particularly in terms of the modulation efficiency.

An order of magnitude improvement is required in the modulation efficiency. It is predicted that improvements of up to 6 dB could be realized through modifications of the existing device design. Realizing the full 10 dB improvement is likely to require major design changes, for example a device based on parallel low drive voltage modulators. Any alternative approach will have to be carefully assessed in order to determine whether it can provide the required orthogonal polarization output, carrier and sideband suppression and modulation linearity.

Millimeter wave applications such as the EHF-RAP and SATCOM require SSB modulators which operate at much higher frequencies. The existing design approach cannot easily be extended beyond about 20 GHz. Alternative approaches are being investigated for millimeter wave optical links but they do not generally provide the specific combination of functions needed in the phased array application.

MIR

The design of the MIR developed in this program has been successful and we would propose that any future build should adopt the same basic technology of a monolithic photodiode array flip chip solder bonded to a microwave transmission line. The extension to a practical device requires effort to improve the fiber interfacing approach, optimize the number of elements in a single device and to produce a good impedance match over a long photodiode-loaded section of transmission line.

Optical Interfacing and Packaging

A complete, optically controlled phased array system is built up using several, separate optoelectronic modules. Within each module there could be several components requiring both optical-optical and optical-electrical interfaces, and further interconnections will be required between the modules. All but the simplest of optoelectronic interfaces are currently performed using active alignment during assembly in order to achieve a low loss, rugged assembly. Due to the large number of such interfaces in a practical phased array antenna system it will be necessary to develop reliable passive or at least semi-passive interfacing techniques for each module. This is a major development exercise which is

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most critical where large numbers are involved, such as interfacing to multi-waveguide devices (e.g., active splitter and splitter / beamformer), and assembly of the T/R modules.

In conclusion, the near term realization of a practical optically controlled phased array RAP antenna requires significant development to only a few critical optoelectronic devices. These include the active splitter and the SSB modulator. The remaining optoelectronic devices require relatively minor improvements in performance or yield. Most of the design and development effort is required in the packaging and optical interfacing to these devices, in particular to achieve reliable multiple fiber interfaces to the splitter / beamformer device and compact low cost packaging of the T/R module components. In parallel with such near term developements, advances in hybrid and monolothic optical integration will be desirable to further reduce the size and cost of an optically controlled phased array antenna system.

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